Interoperability

GMLC Foundational Project 1.2.2

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Context

Too many devices and systems today cannot interoperate or require difficult and time-consuming integration processes. This results in fewer deployed new technologies (including Distributed Energy Resources - DER) and higher costs.

Key Objectives:

- Advance adoption of interoperable products and services in the energy sector.
- Align stakeholders on a strategic vision.
- Develop measures and tools to support interoperability.

Partner Involvement

Advancing interoperability requires stakeholder alignment; it's a shared challenge. To achieve alignment, the project regularly meets with 16 industry partners and holds events with industry to provide critical review of ideas and incentivize industry involvement to simplify integration.

Declaration of Interoperability

About 50 people from a cross section of industry met to create a "declaration of interoperability" that lays out a common definition of interoperability, problems caused by poor interoperability, and a commitment to advance interoperability. This involves changes to integration technologies and business processes within sectors and across them.

Industry Tech Meetings

Held meetings in Chicago, Ill (Sep '16) and Columbus, OH (May '17) with industry participants that advanced criteria for interoperability, enhanced integration vision stories, and affirmed project directions.

Participants offered diverse perspectives on challenges and goals that tested universal concepts and principles.

Trial Roadmaps

The project is engaging 2 ecosystems integrating DER to use the strategic vision, interoperability measurement and roadmap methodology to test and refine these tools

- IEEE 2030.5 Ecosystem Steering Committee formed. June '18 meeting in Los Angeles
- EC Joint Research Centre (JRC) ecosystem on EV charging

Procurement Language

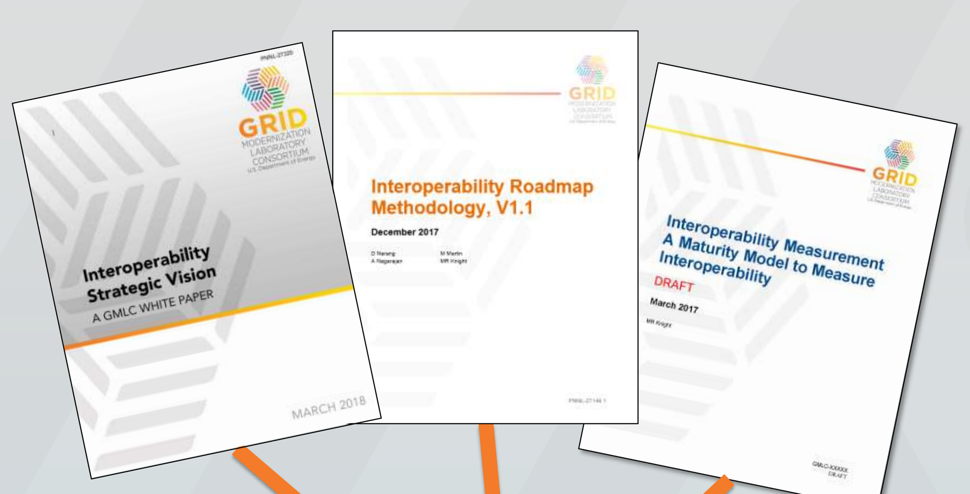
The interoperability measurement criteria in the IMM inspire performance statements that can be a model for the procurement of smart technology. We are working with SEPA and other partners to create tools that incentivize industry involvement.

Expected Outcomes

- Establish an interoperability strategic vision.
- Describe the state, challenges, and path forward to advance interoperability.
- Offer tools to facilitate gap analysis, develop roadmaps, and demonstrate visionary concepts

Project Outreach

Engagements held at GWAC, IEEE ISGT, IEEE PES, SEPA Grid Evolution Summit, IEEE T&D, Transactive Energy Systems, and AHR Expo events. Project information has been circulated in the SEPA, NIST, and LonMark newsletters. Public Utilities Fortnightly (Apr '17) and Smart Grid Newsletter (Jun '18) featured articles about this project.



Deliverables to Date

This project provides leadership visibility to DOE as a champion for grid modernization interoperability with a number of deliverables, including:

- Strategic Vision Whitepaper
- Roadmap Methodology
- Interoperability Maturity Model (IMM)

Interop Challenge

PLUG & PLAY DER CHALLENGE

Engage industry to propose and demonstrate new ideas to advance interoperability

- Phase 1: concepts that significantly improve interoperability for DER Integration – Launched July, presentations at Solar Power International Sep '18.
- Phase 2: demonstrate accepted concepts, mid '19
- Set course for standards convergence with partners

GMLC 1.2.3: Testing Network and Open Library

PI: Matthew Lave (Sandia), +1: Rob Hovsapian (INL)
Project Team: Sandia, INL, LBNL, NREL, ORNL

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Access to testing resources and models at National Labs and beyond is vital to grid modernization.

We are improving access to testing infrastructure for grid devices and systems, and related models and tools:

- **Testing Network (GMLC-TN):** a federated, lab-based resource for testing and performance validation of grid devices and systems
- **Open Library (GMLC-OL):** a public repository for validated models, simulation tools, testing resources

Project Team

Sandia National Laboratories	Idaho National Laboratory	NREL, Oak Ridge National Laboratory, Berkeley Lab
Project lead, Lead for TN task	Co-PI, Lead for OL task	Support TN and OL: outreach; sustainability; collect models, tools, and testing resources

Project Progression/Milestones

PY1 – Establish Foundations

- Held stakeholder workshop to solicit feedback
- Performed initial identification of Lab capabilities
- Studied and engaged existing consortia

PY2 – Deploy the TN and OL

- Published testing resources catalog
- Populated OL with models from National Labs/GMLC
- Established gridPULSE consortium (covers TN and OL) through a membership agreement and website

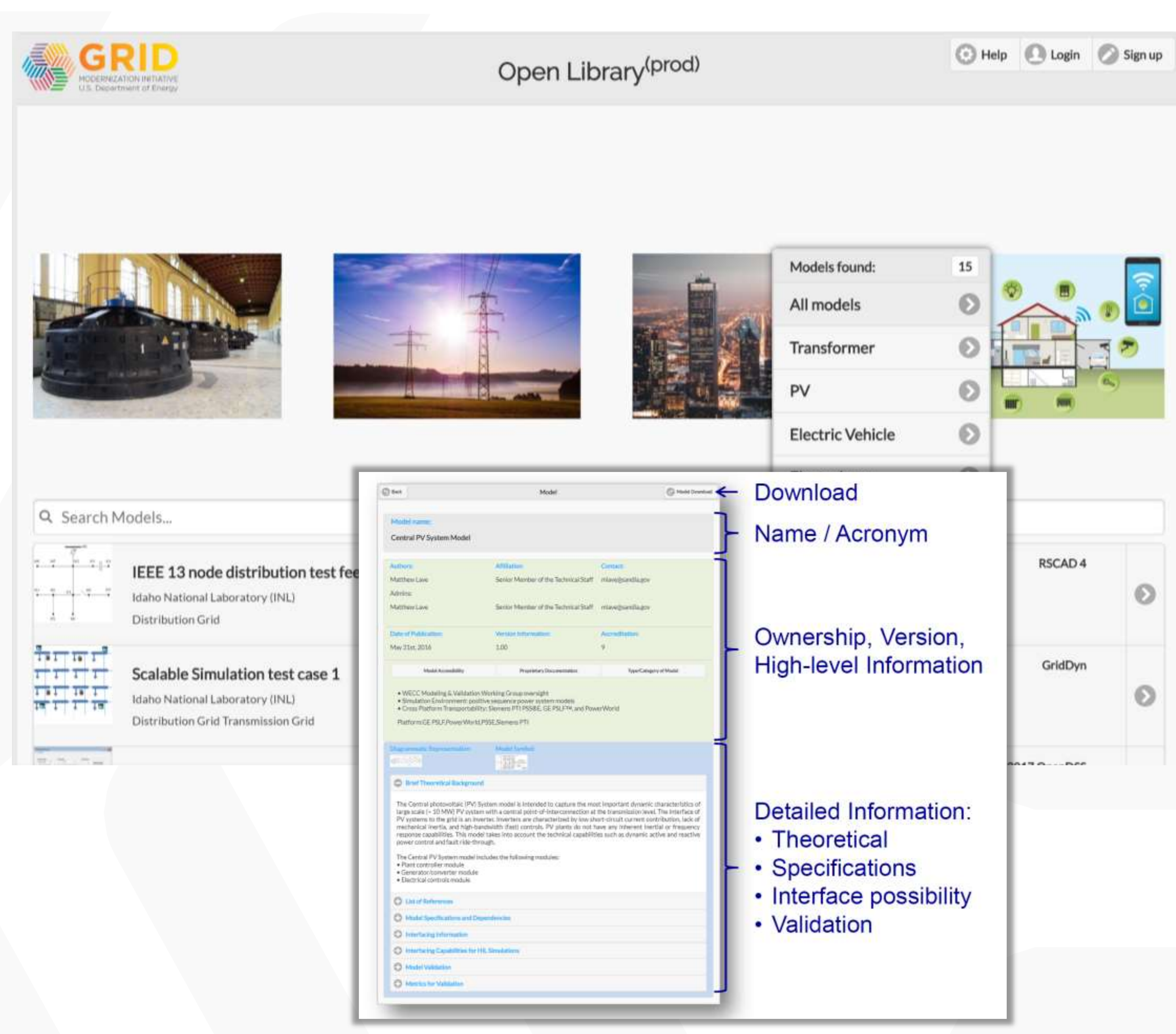
PY3 – Ensure Future Sustainability

- Developing sustainability plan with value proposition
- Outreach including conferences and webinars
- Expanding OL to increase value, improve usability

Accomplishments to Date

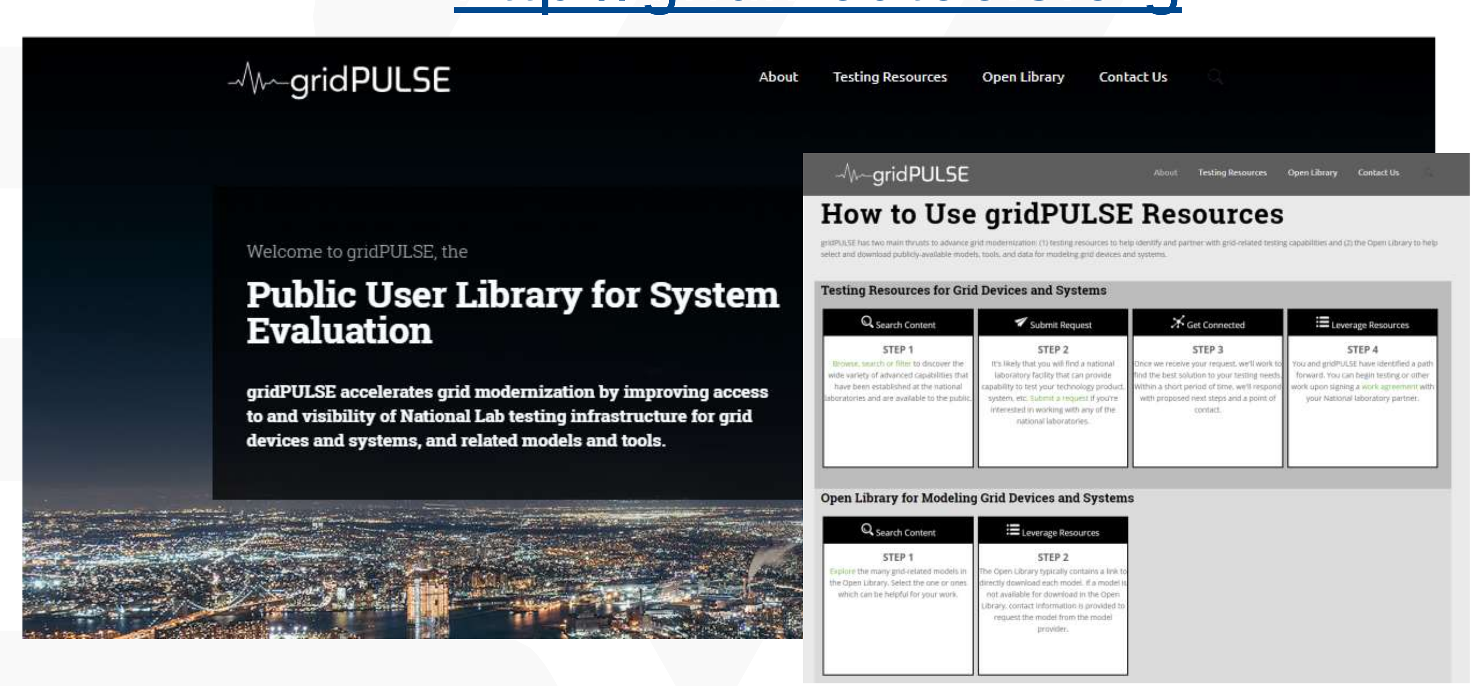
Testing Resources Catalog

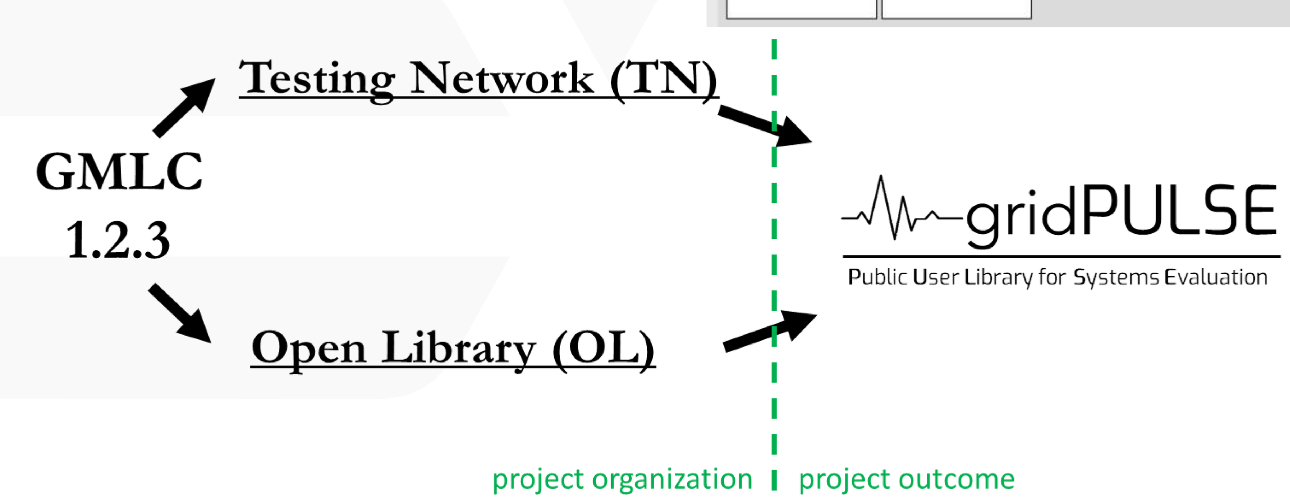
Open Library Implementation



Consortium and Website

http://gridmodtools.org





Expected Outcomes

- Greater understanding, awareness, access to Lab capabilities
- Go-to resource for validated models, tools, test procedures
- Improved collaboration among facilities
- Accelerated adoption of new grid devices

U.S. DEPARTMENT OF ENERGY

Fast Grid Frequency Support from DERs

GMLC 1.3.29 – Hawaii Regional Partnership

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

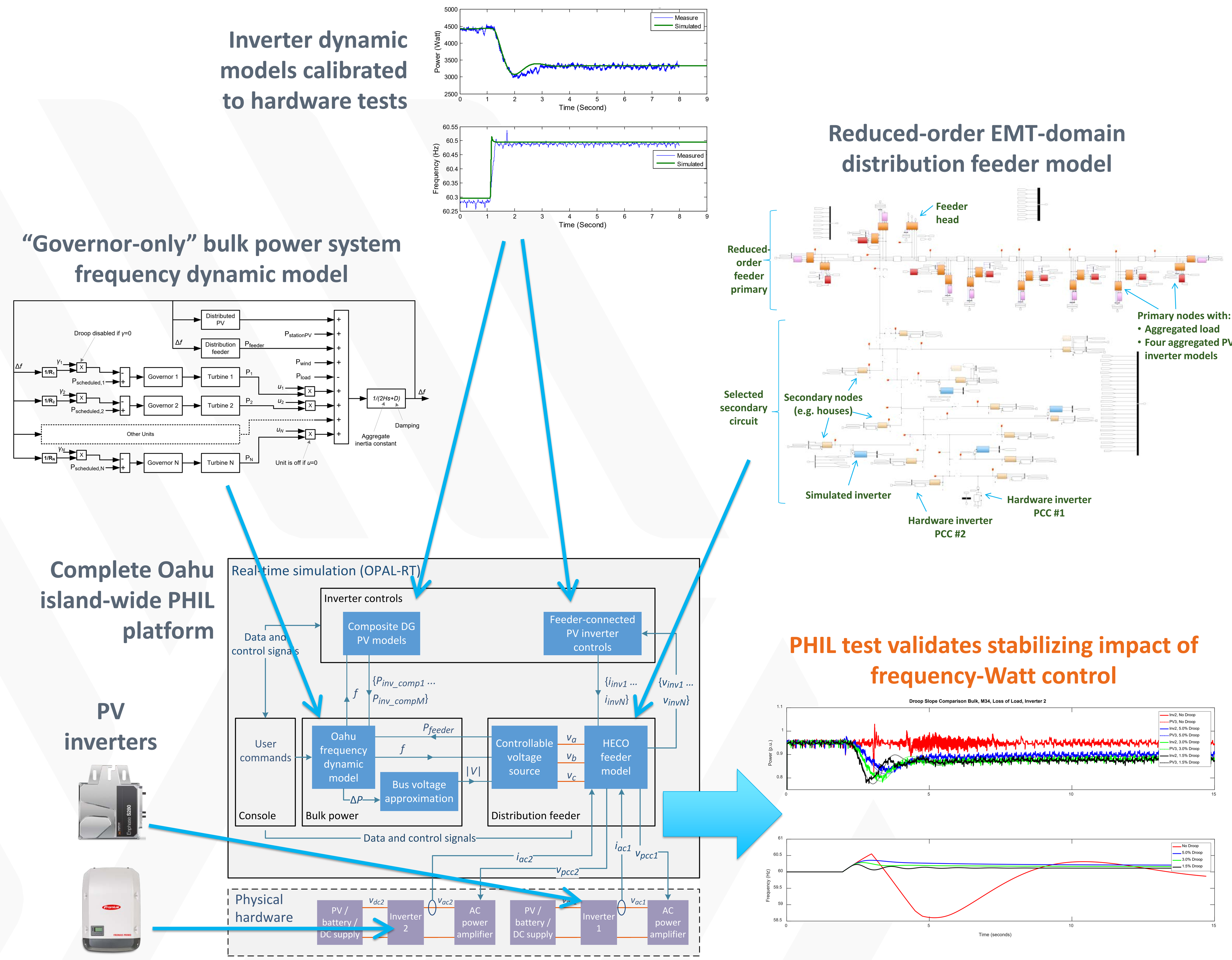
Project Description

Hawaii leads the US in the portion of its electricity produced from distributed PV, forcing it to confront emerging grid reliability issues sooner than other states. PV systems have displaced many of the conventional generators whose inertia and governor controls help to stabilize the grid. NREL and Sandia partnered with the Hawaiian Electric Companies (HECO) and key stakeholders to **investigate, develop, and validate ways that DERs can support grid frequency stability on the fastest time scale (cycles to seconds)**.

Outcomes

- Enable distributed PV and storage inverters to support grid frequency starting a few AC line cycles after the appearance of a frequency event
- Validated DER frequency support via conventional simulation (PSSE) and power hardware-in-the-loop (PHIL) testing – first ever system-wide transient time-scale PHIL platform (figure at right)
- Forged a path for rest of U.S. to follow towards frequency-responsive DERs, helping ensure future grid reliability

Significant Milestones	Date
1.2 - Simulated Oahu frequency events show DER-based frequency support avoids load shedding	Sept 2016
2.4 - Prototype inverter controls for improved frequency support demonstrated	March 2017
3.6 – Island-wide PHIL model validates hardware inverter frequency response	Dec 2018



Progress to Date

- **Hawaii PUC approved** revised interconnection standard (Rule 14H) **activating frequency-watt control system-wide** (October 2017) using **settings recommended in project team's technical report**
  - HECO and NREL addressed DER industry concerns through broad stakeholder process (AIFWG)
  - HECO is first US utility to activate f-W control system-wide
  - California to activate f-W control as well in February 2019
- Project findings justified **modification of IEEE 1547 national standard to allow very fast (sub-second) frequency support**
- Nine publications so far, including:
  - **New inverter control method** for rapid active power control of PV systems: Hoke et al, *IEEE Journal of Emerging and Selected Topics in Power Electronics*, Sept 2017
  - IEEE **PES General Meeting Best Paper:** Nagarajan et al, "Network Reduction Algorithm for Developing Distribution Feeders for Real-time Simulators", IEEE PES GM, 2017
  - **Detailed inverter model for PSSE simulations:** Pierre et al, "PV Inverter Fault Response Including Momentary Cessation, Frequency-Watt, and Virtual Inertia," IEEE PVSC, 2018

Standards & Test Procedures for Interconnection & Interoperability

Updating DER Integration Standards for the Modern Grid (GMLC 1.4.1)

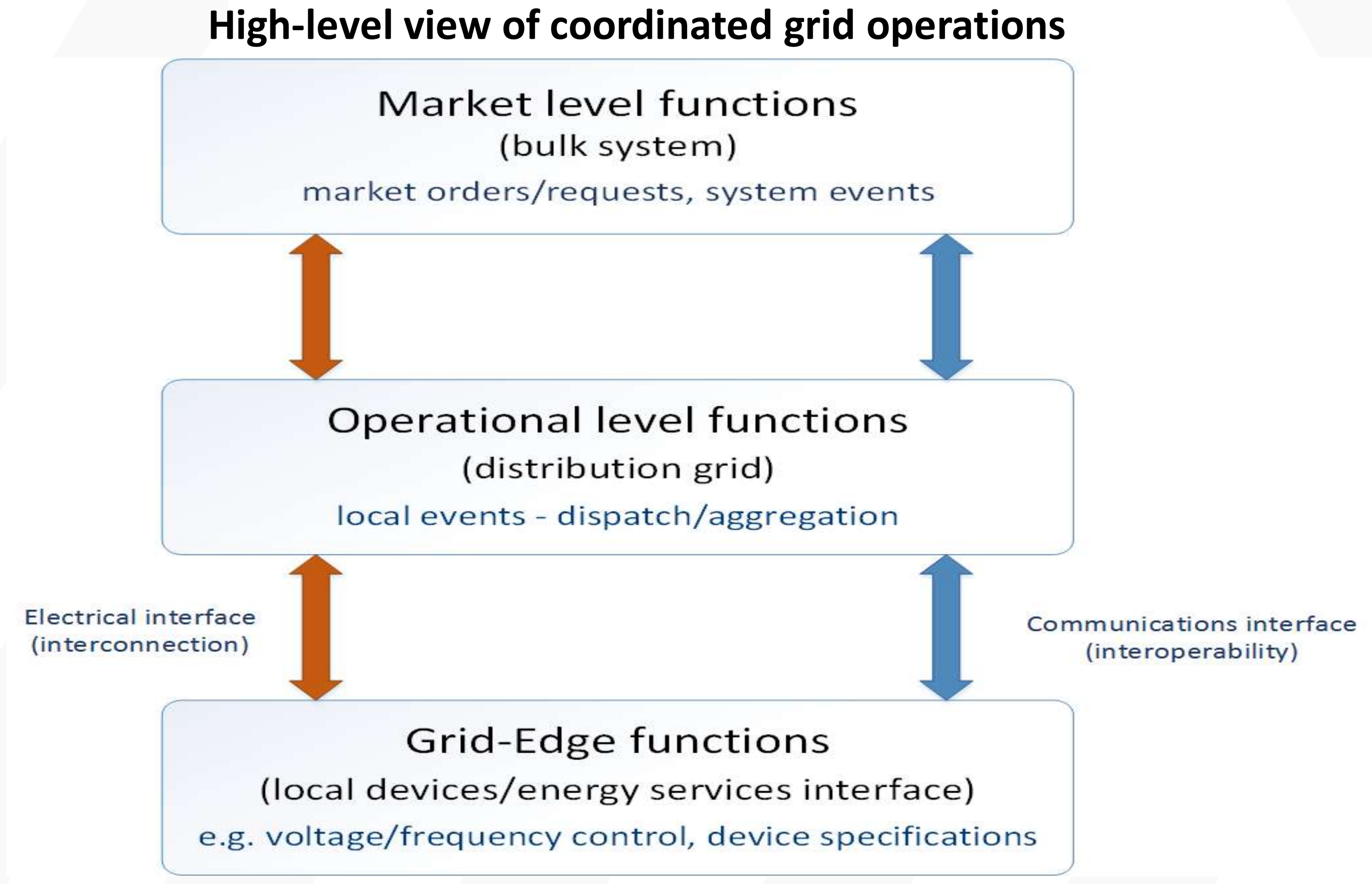
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

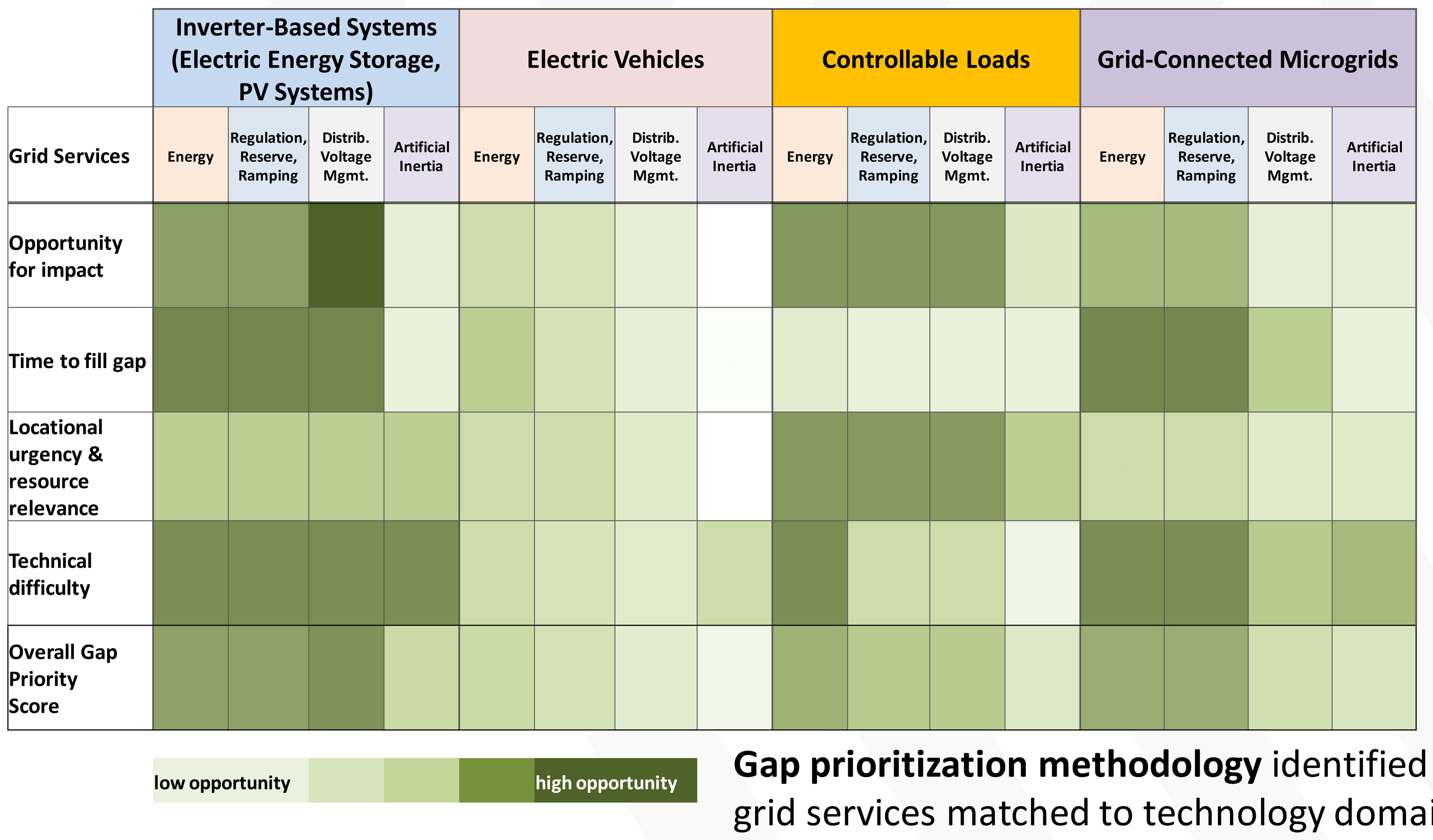
Project Description

- **Accelerate** DER interconnection & interoperability standards development & validation
- Ensure **cross-technology compatibility** & harmonization of requirements for key grid services
- **Minimize conflicting** requirements across technology domains

Expected Outcomes

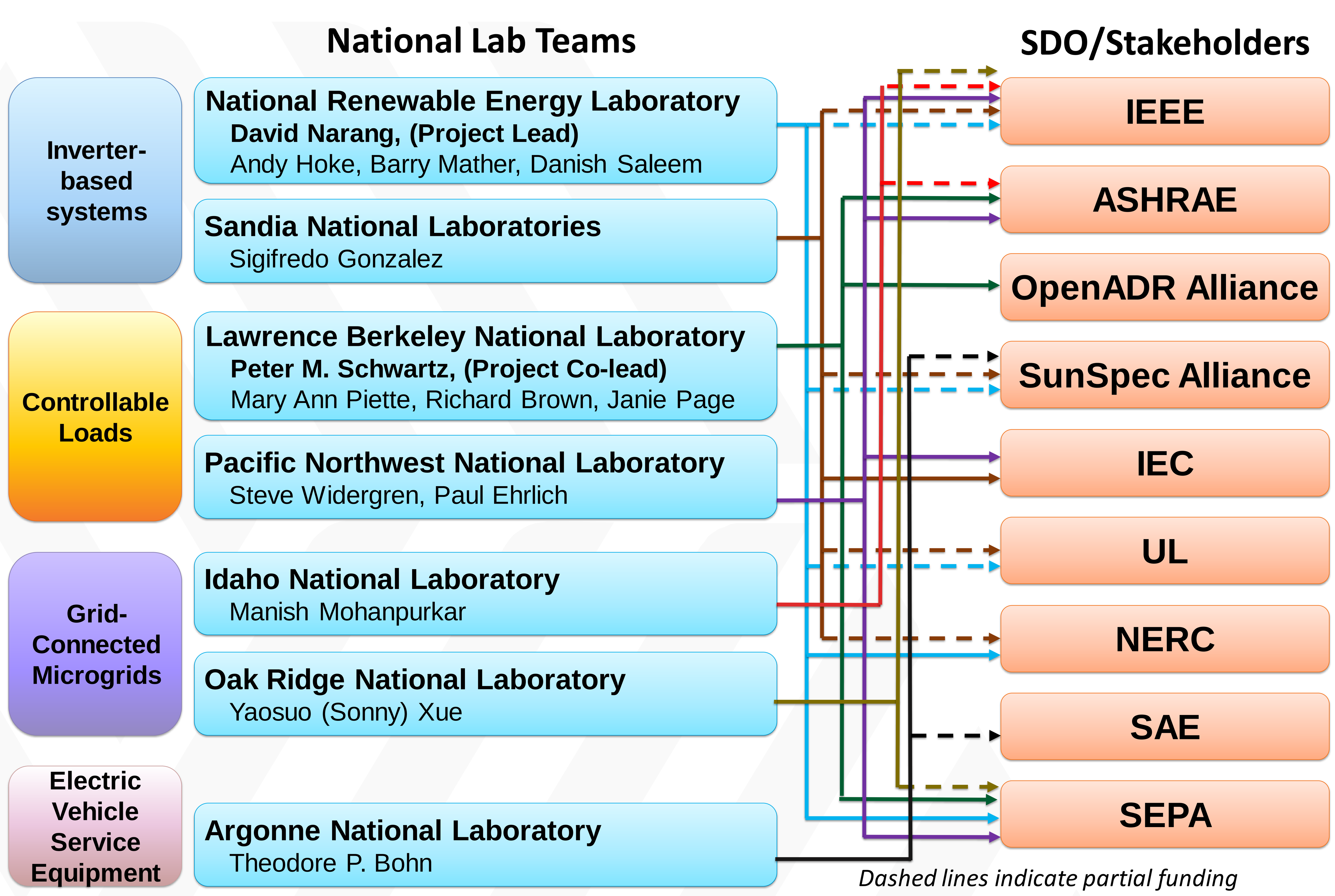
- **Improve** modern energy generation & storage devices' **coordination** with the grid
- **Enable market expansion** through improved interoperability
- **Reduce barriers** to deployment through improved standards





Gap prioritization methodology identified key grid services matched to technology domains.

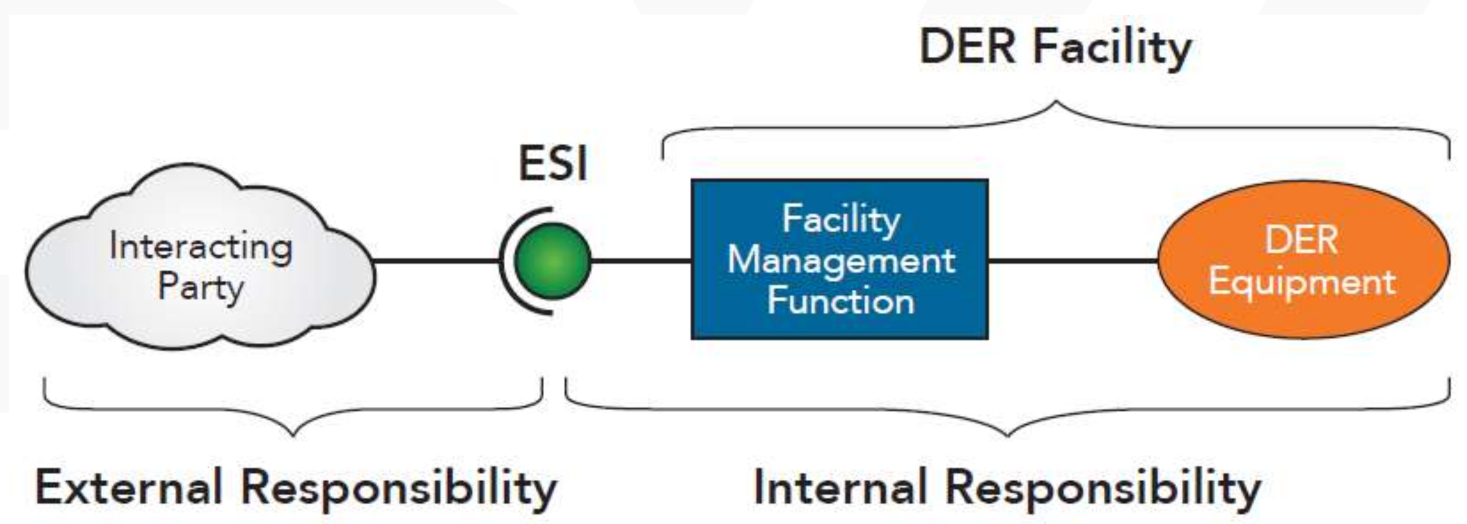
Team Contributions to Standards-Related Activities



Dashed lines indicate partial funding

Collaboration Opportunity

Requirements for Energy Services Interface



High level diagram of ESI and related functions (courtesy S. Widergren, GMLC 1.2.2)

Progress to Date / Significant Milestones	Date
Gap prioritization framework	Mar 2016
Preliminary gap analysis, including identification of key standards	Sep 2016
Stakeholder Workshop: GMLC	Sep 2016 (Denver CO)
Stakeholder Workshop: SEPA 2016 Grid Summit	Nov 2016 (Washington, DC)
Peer Review: Share results & recommendations	April 2017 (Washington, DC)
Share results with select industry advisors, improve gap analysis	Apr – Jul 2017
Peer Review: Share results & recommendations	Feb 2018 (Washington DC)
Stakeholder Workshop: Energy Services Interface (ESI)	May 2018 (LBNL – webinar)
Collaboration with SEPA on ESI requirements	Sep 2018

GMLC 1.4.2: Definitions, Standards and Test Procedures for Grid Services from Devices

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Develop and test high-resolution models of distributed energy resources (DERs) with a **standardized interface in the form of a battery-equivalent representation**, for

… ready access by planning and operational tools used to assess DERs' ability to provide operational flexibility in the form of valuable grid services

… at the bulk system and local distribution levels.

Expected Outcomes

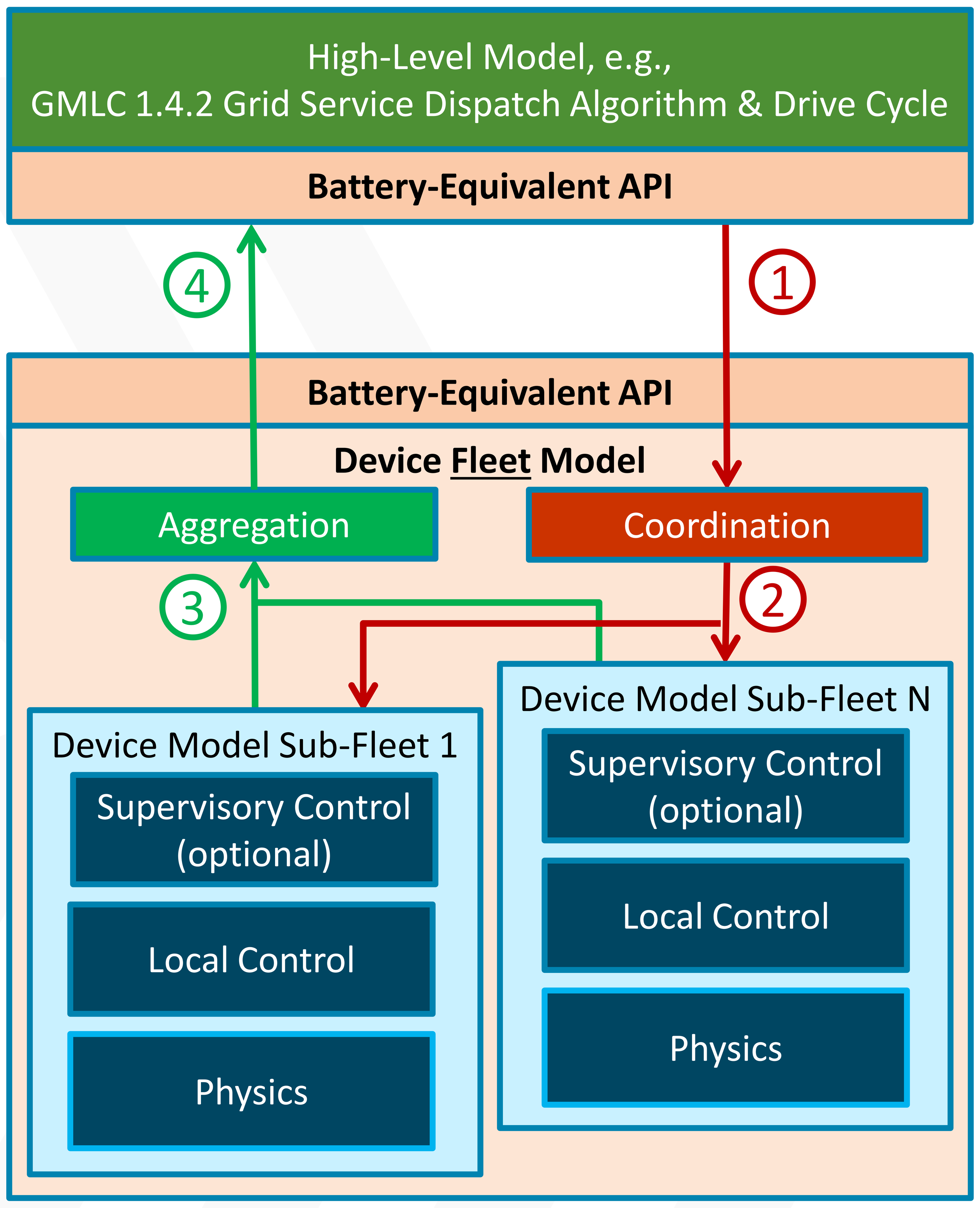
High-resolution DER models in Python

- ✓ Explicitly model engineering, operational, & human constraints

Common battery-equivalent representation allows:

- ✓ Operations & planning models easily & accurately assess DERs
- ✓ Resources from DER classes to be "summed"
- ✓ Grid control & optimization methods to be shared across DER types
- ✓ Level-playing field for evaluating DERs
- ✓ Consideration as a grid flexibility metric

Significant Milestones	Date
Implement device model and battery equivalent interface in software	July 31, 2018
Specify device characterization tests	July 31, 2018
Recommendations for additional tests or results from appliance standards testing	July 31, 2018
Document grid services/drive cycles, device models, battery equivalent interface, results of trial analysis	Sep. 30, 2018



Software architecture of services and device models. Device fleets are composed of individual devices representative of diversity in population and usage.

Progress to Date

- Technical report: device models & grid services
- Two workshops, targeted webinars with device & grid industries
- GitHub library of models & services in Python
- Integration of services & models underway
- Draft report: Opportunities to leverage & extend DOE efficiency standard's tests for device DER characteristics
- Draft device testing plan for water heaters, electric vehicles, & commercial refrigeration

LPNORM: A LANL, PNNL, and NRECA Optimal Resiliency Model

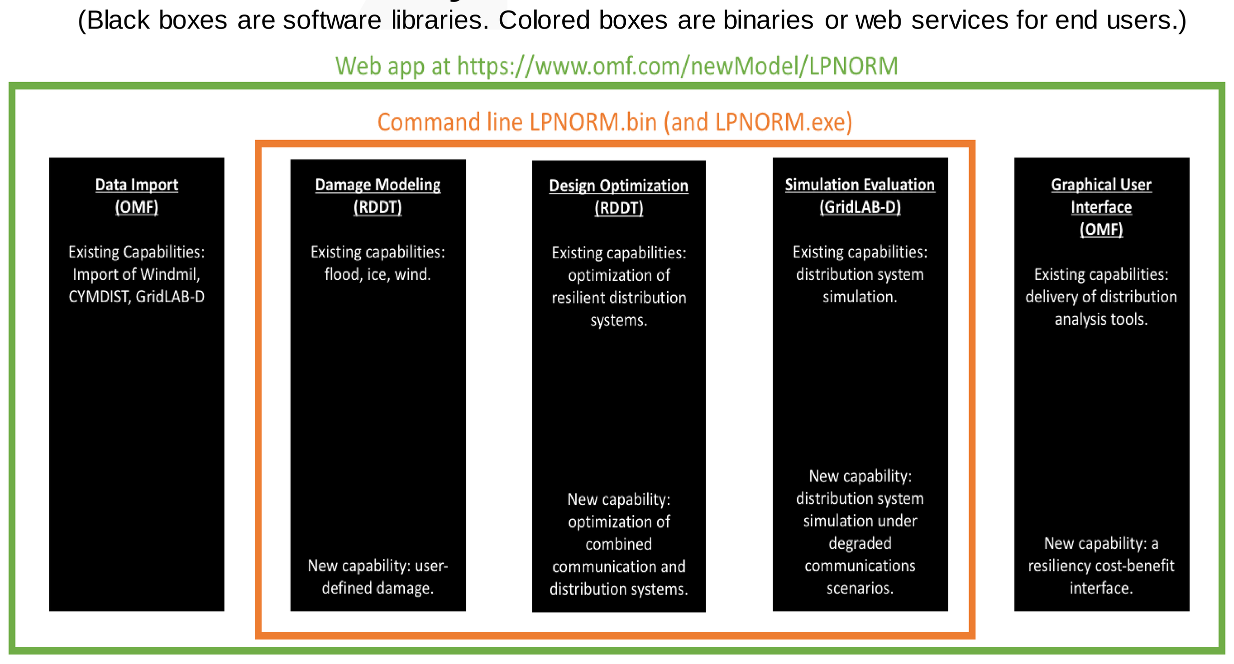
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

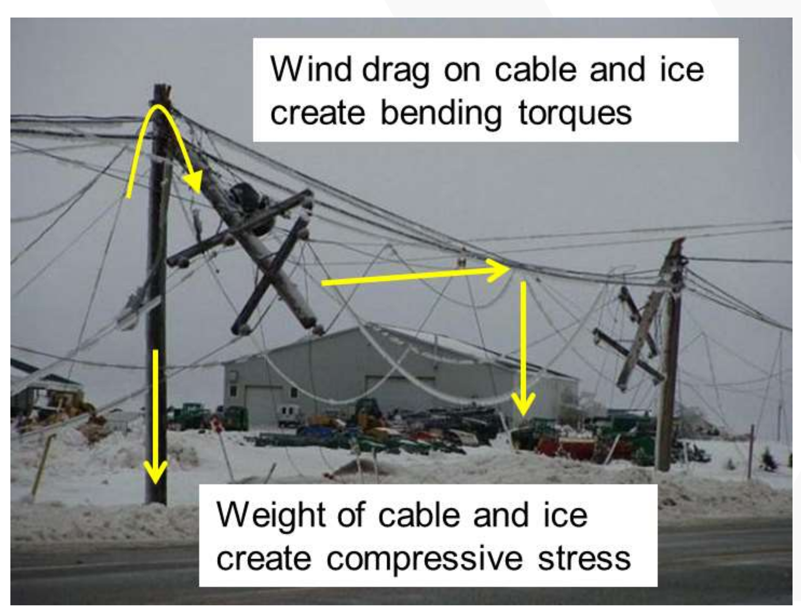
Project Description

- Extreme weather events pose an enormous threat to the nation's electric power distribution systems
- Distribution utilities lack the tools to help them plan for extreme events.
  - Resiliency assessment
  - Extreme event impact mitigation
- This project develops LPNORM to design resilient distribution systems
  - Import distribution and communication models
  - Specify extreme events
  - Specify resiliency criteria
  - Verify design solution quality with trusted power flow solvers

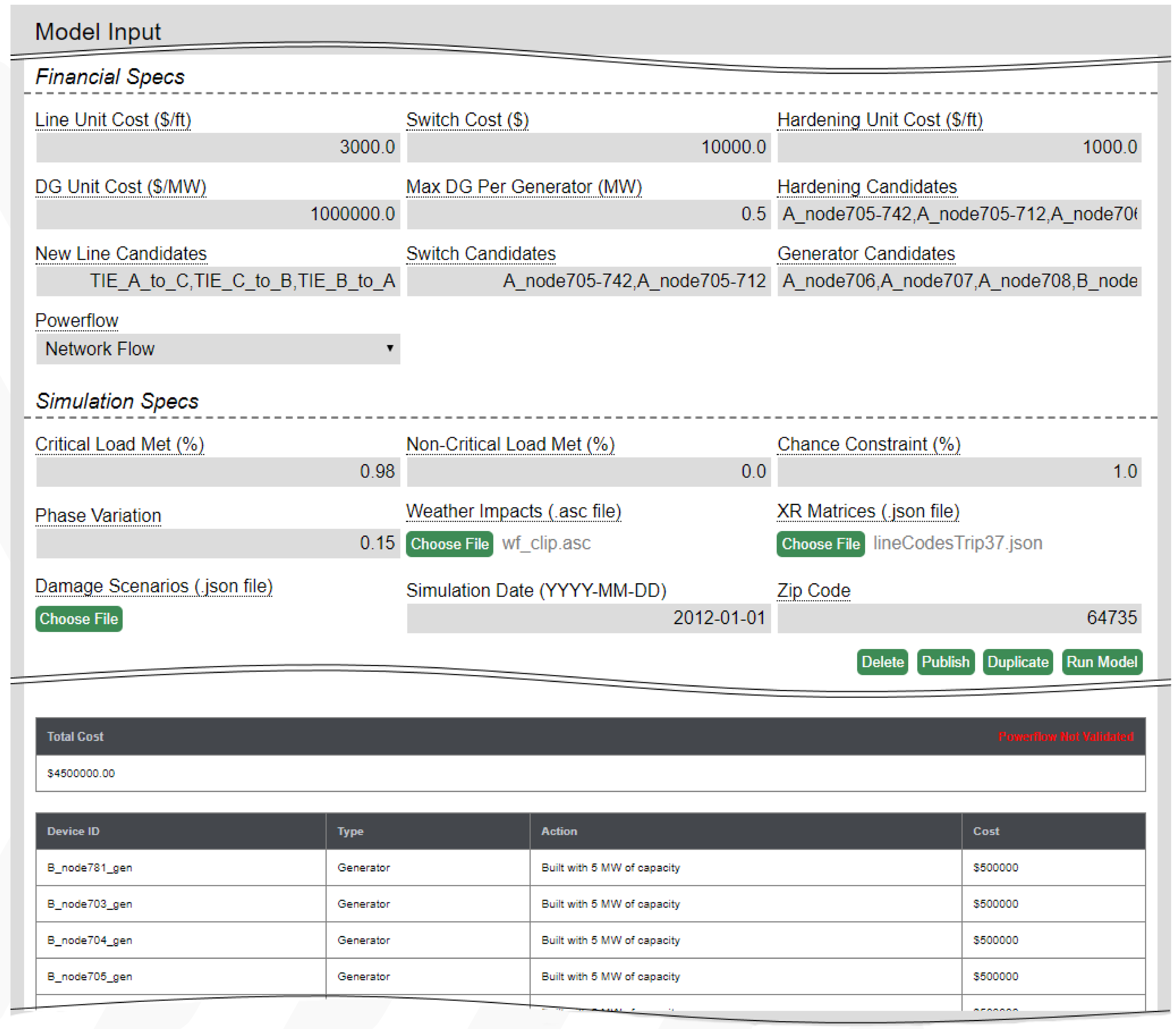
LPNORM System Architecture Sketch

(Black boxes are software libraries. Colored boxes are binaries or web services for end users.)





LPNORM User Interface via OMF



Expected Outcomes

- An open source software tool that combines NRECA 's Open Modeling Framework (OMF), distribution power system data, LANL's General Fragility Modeling (GFM), LANL's Resilient Design Tool (RDT), and PNNL's distribution power flow tool (GridLAB-D)
- Design systems that can serve up to 98% of critical load during extreme events

Significant Milestones	Date
Demonstration of RDT integrated with OMF distribution system models	10/1/16
LPNORM demonstrated with existing LANL (RDDT), PNNL (GridLAB-D), and NRECA (OMF) capabilities for a single hazard	4/1/17
Alpha version of LPNORM released for review by the utility user group	10/1/17
Peer reviewed paper on communication and distribution system algorithm	4/1/18
Choose two NRECA member utilities to participate in demonstration, beta version released for their participation	10/1/18
Report on user experience and beta tool released on NRECA's Open Modeling Framework	4/1/19

Progress to Date

- Released Alpha version (October 2017) https://www.omf.coop/newModel/resilientDist/lpnorm
- Detailed data collected from the Industry Advisory Board
- Increased industry engagement with additional utility interest: Orange and Rockland, an investor-owned utility (IOU)
- Two utilities selected for Beta version testing: Shenandoah Valley Cooperative and United Cooperative Services
- Related Publications
  - G. Byeon, H. Nagarajan, R. Bent, P. van Hentenryck. *Communication-Constrained Resilient Distribution Grid Design*, submitted to the INFORMS Journal of Computing
  - A. Barnes, H. Nagarajan, E. Yamangil, R. Bent, and S. Backhaus. *Resilient Design of Large-Scale Distribution Feeders with Networked Microgrids*, submitted to Applied Energy.

Distribution Transformer Data, Testing, and Control

Jamie Lian, PNNL
Klaehn Burkes, SRNL

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

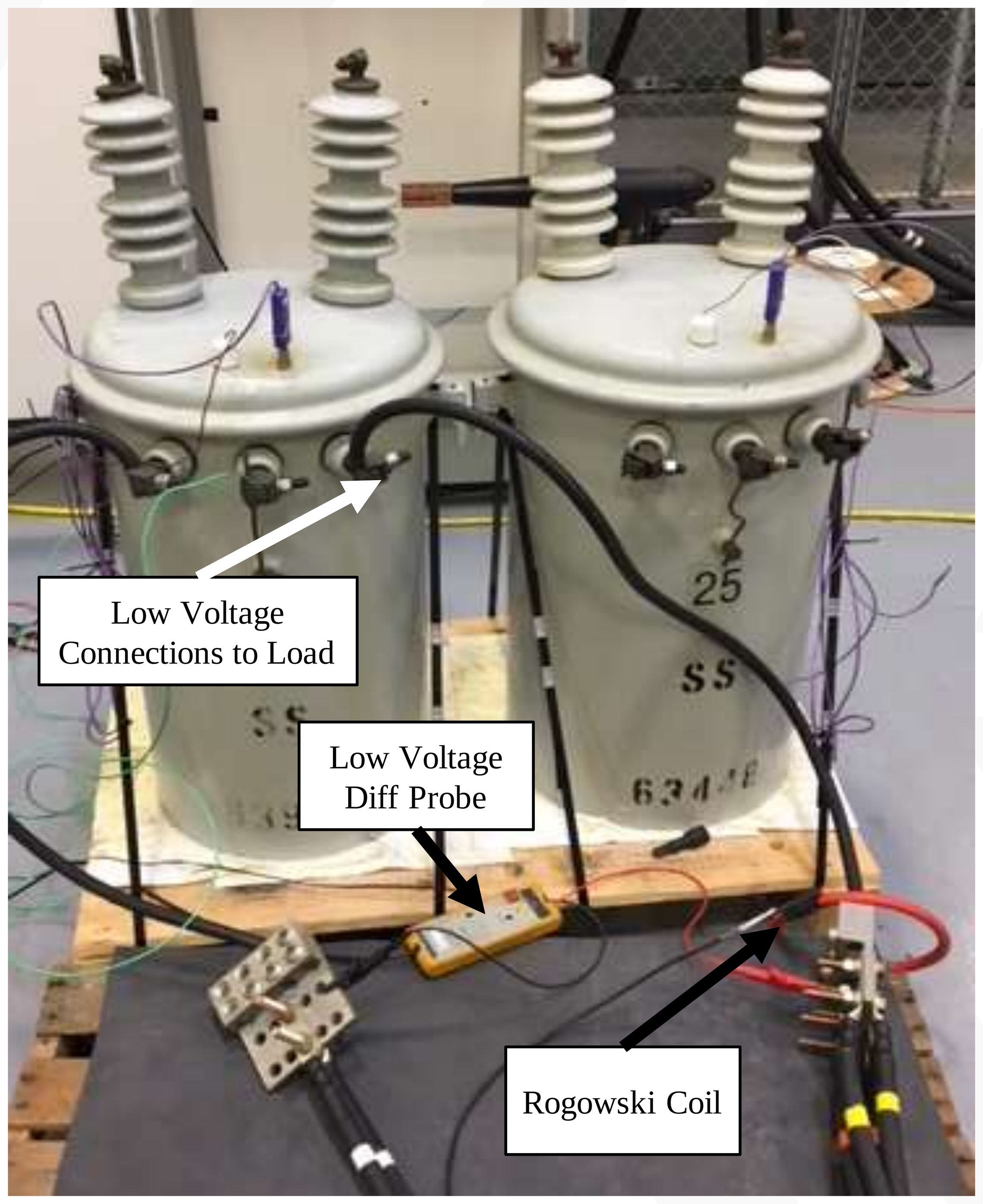
Advance the state-of-the-art technologies of transformers with novel approaches

Provide proven guidance for the U.S. concerning the opportunities to reduce transformer losses and to prolong transformer lifetime

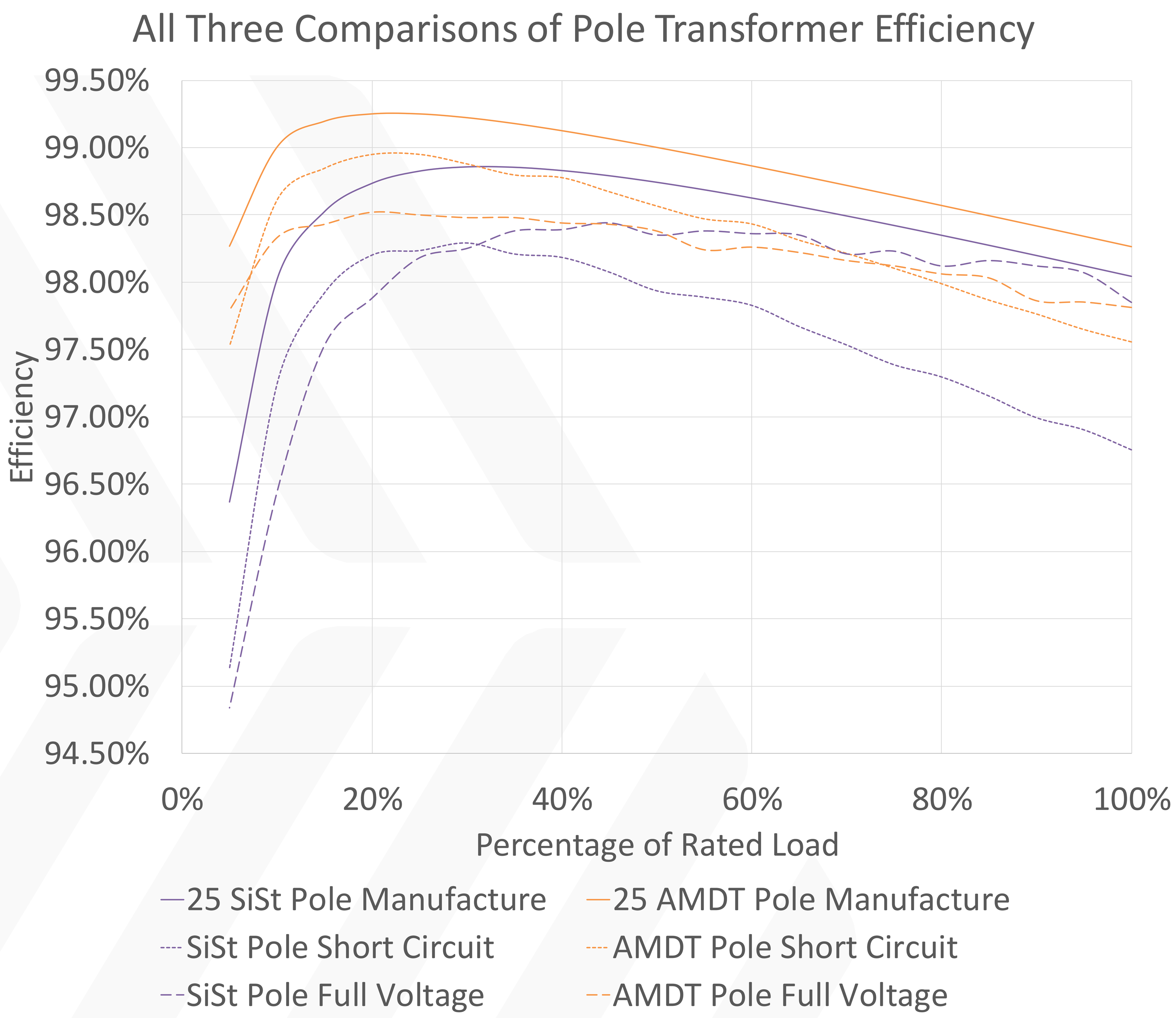
- ► No-load loss reduction from the adoption of amorphous metal core transformers leads to efficiency improvement
- ► Lifetime improvement from the adoption of transactive coordination and control for transformers and their loads

Expected Outcomes

- Distribution transformer losses account for 2–3% of U.S. generated electricity, and no-load losses represent approximately 25% of these losses.
  - Adoption of more efficient transformers could reduce no-load losses by 60%
    - Project will assemble data addressing market barriers that impede this adoption
  - Dynamic control and coordination of transformers and building loads could reduce losses by 10%
    - The project will scope control strategies that might deliver this benefit



Significant Milestones	Date
Develop Report on Utility Data - complete	July 2017
Develop Test Plan for Distribution Transformers - complete	May 2018
Report Documenting Testing – on track	September 2018
Closed-Loop transactive control optimization – on track	December 2018



Progress to Date

- Tested two pairs of Distribution Transformers
  - Establishes functional acceptance, efficiency baseline, sweeping tests of efficiency under harmonics, and degradation over time
- Santee Cooper sharing 20 years of performance and cost data
  - Report was developed documenting transformer population
- Identified six innovative control strategies to be scoped and analyzed
- Developed open-loop transactive control to improve transformer life though reducing hottest-spot temperatures
- Transactive load control increases transformer lifetime by 6.15, 16.24 and 19.13 years, respectively, corresponding to three capacity limits

PNNL-SA-137697

Collaborative Demo for Secondary Use and Use Case Validation

Lead: Oak Ridge National Laboratory
Partners: Spiers New Technologies, Chatham Habitat for Humanity

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

OBJECTIVES

- Developing a low cost energy storage system for communities using repurposed vehicle batteries.
- Deploying energy storage system with rooftop PV into a residential building supplied by Habitat for Humanity.
- Evaluating economic feasibility of the technology moving forward and developing appropriate tools.
- Creating a workforce education program for future technicians.

CHALLENGES

- New energy storage technology associated with electric vehicles has exposed a gap in residential energy storage system controls.
- Certification of 2nd life automotive battery storage systems has been difficult as differing regulatory domain exists.
- Secondary-use batteries exist in many grades and must be evaluated and sorted to be packaged into a single system with minimal handling to be cost effective.
- Understanding the value proposition of these deployments with complicated rate structures and use cases that do not have sufficient support.

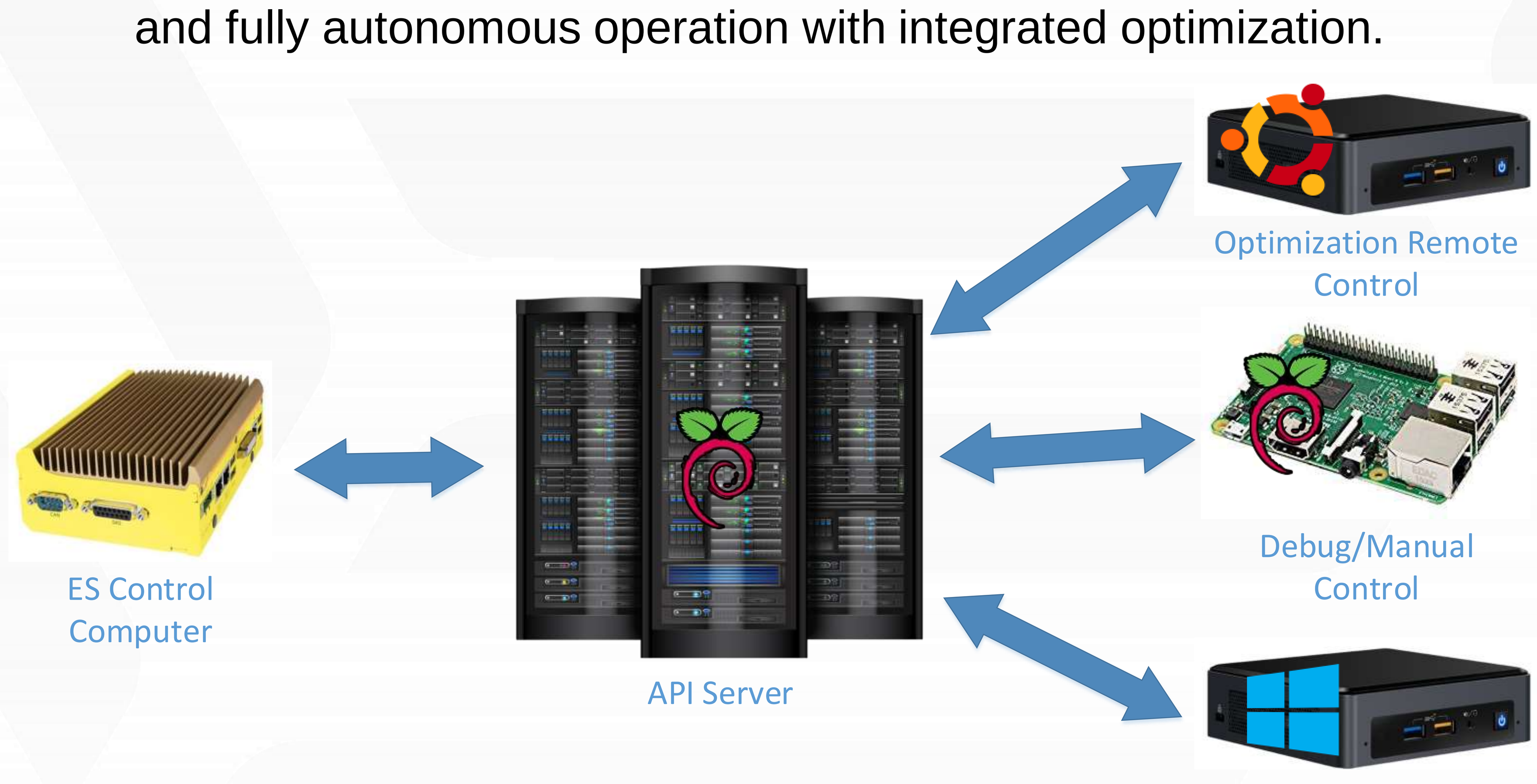
RESEARCH AND DEVELOPMENT

Certification Process

- Module UL certification for batteries already exists with Nissan. Team is working on developing the process to transfer UL certification from first life to second life applications via lab testing and demonstration.

Remote Monitoring and Control

- Developed a JSON based API for remote data collection and control of the ESS.
- Developed front-end software interfaces which can provide varying levels of remote control: debug/manual control, use-case testing, and fully autonomous operation with integrated optimization.



CONCLUSION AND NEXT STEPS

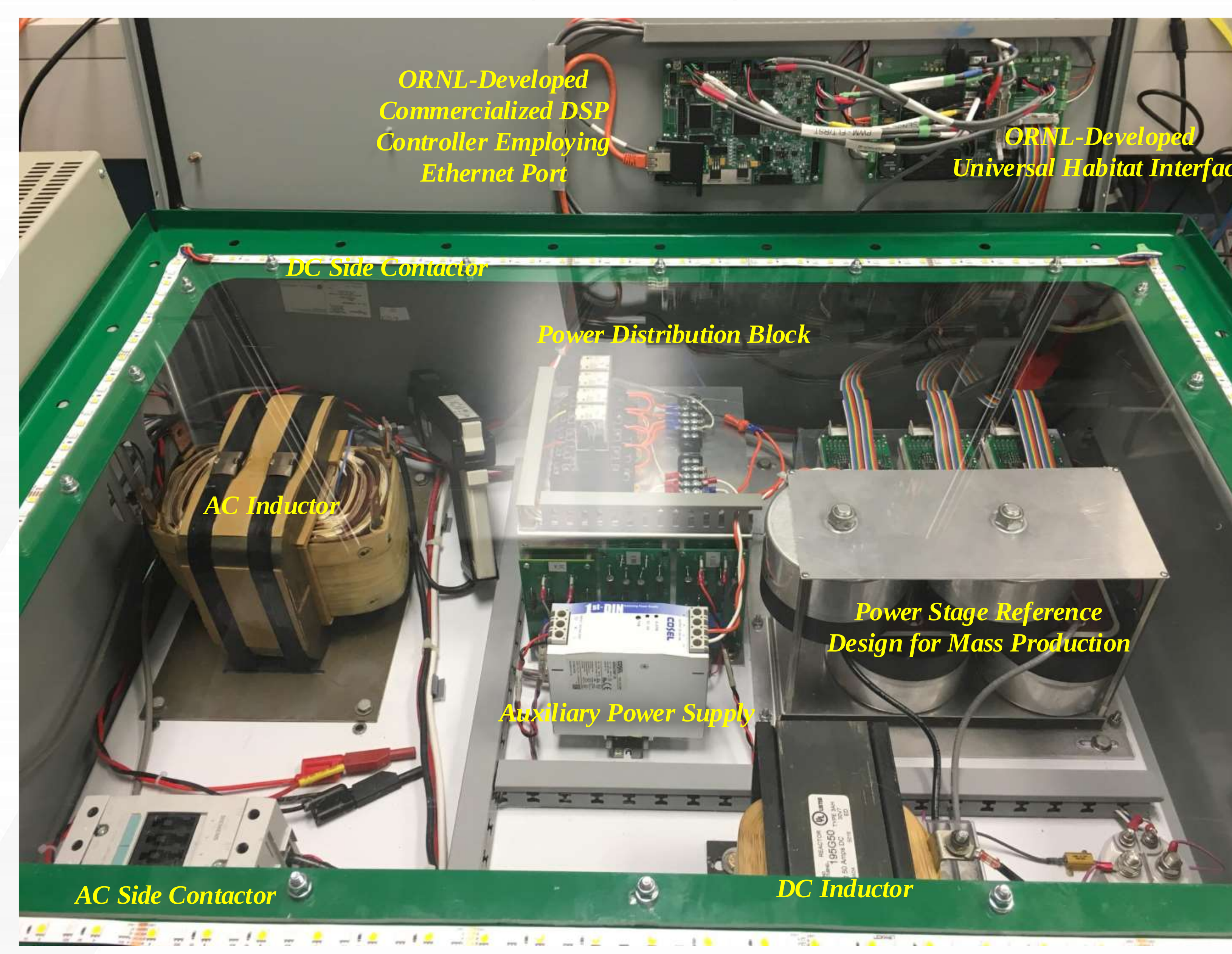
- Successfully demonstrated a 10 kW, 16 kWh low-cost residential energy storage unit using secondary-use batteries
- Integrated various inverter hardware to demonstrate flexibility of the control hardware
- Full deployment at a Habitat for Humanity house in North Carolina to follow in the next few months.

Developments of Habitat Generation II Reference Design

- Dedicated design adopting off-the-shelf components to further reduce the hardware cost and guarantee availability and sustainability for the future mass production.
- Achieved 10 kW bidirectional power flow between battery and grid.

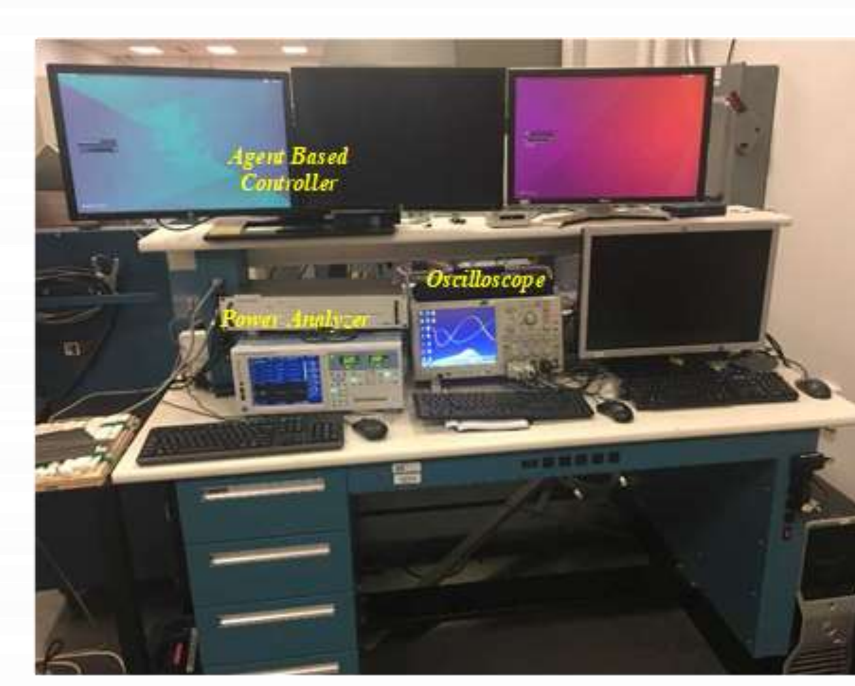
Key Accomplishments

- Developed cost-efficient commercialized solution of converter level controller with Ethernet access.
- Evaluated the reference design continuously in real grid-tied environment.
- Implemented several use cases and ready for the field deployment
- Verified autonomous remote operation capabilities.

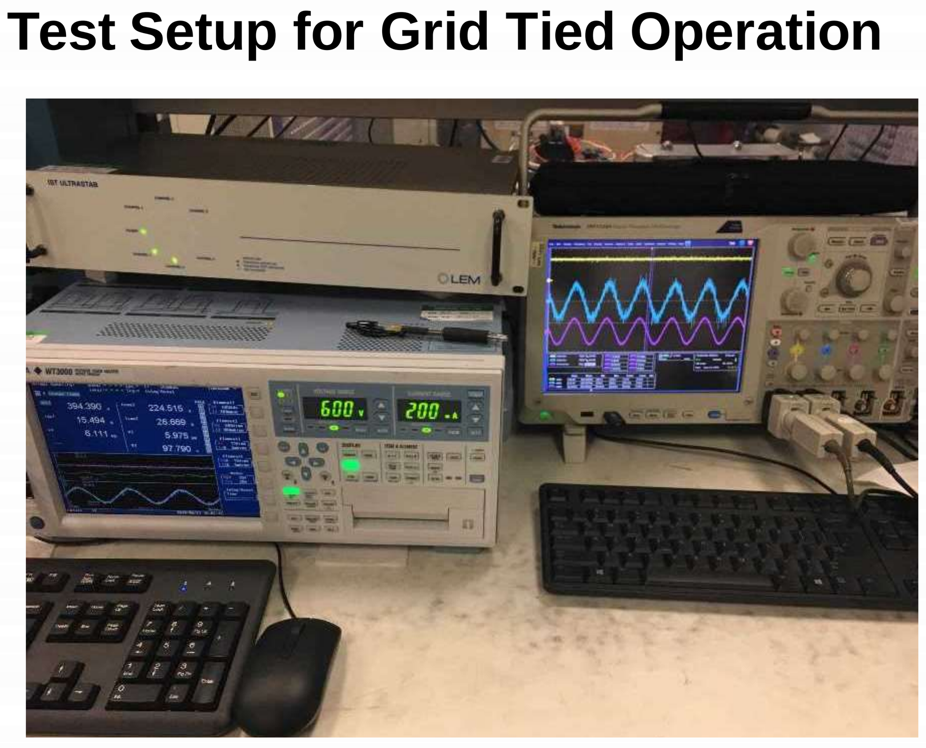


Habitat Generation II Reference Design for Low Cost Mass Production

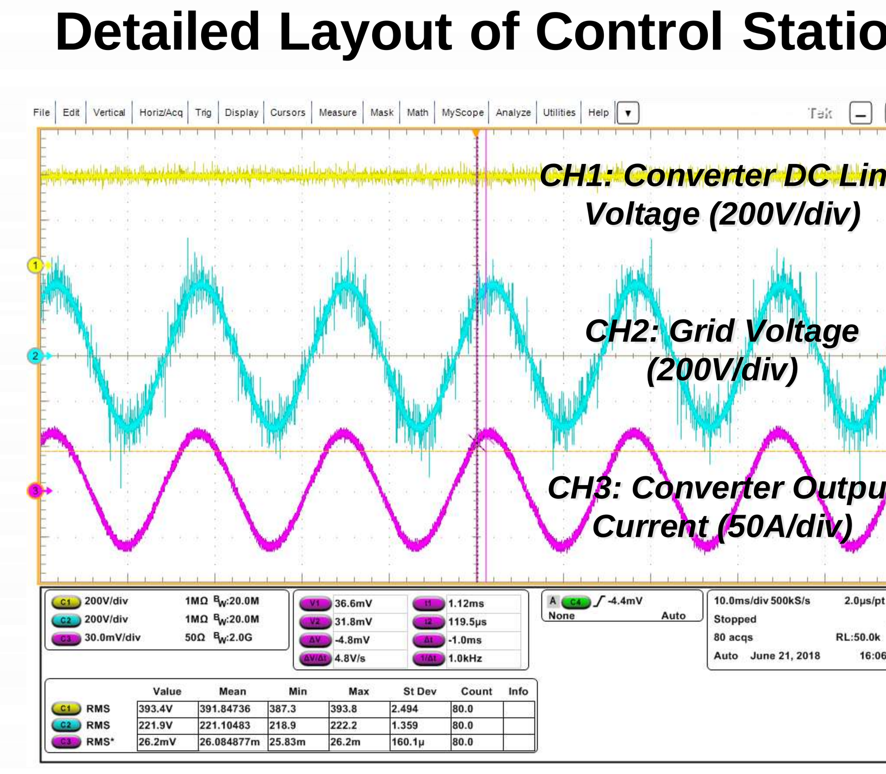
Test Setup for Grid Tied Operation



Detailed Layout of Control Station



Displays on Power Analyzer and Oscilloscope During Grid Tied Test



Experimental Waveforms Captured by the Oscilloscope During Grid Tied Test

GM0204: Universal Hybrid Inverter Driver Interface for VOLTTRON™ Enabled DER Power Electronics Applications

Lead: Oak Ridge National Laboratory

Team: Pacific Northwest National Laboratory

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

- Enable near real-time control and integrate renewable-energy-based power electronics inverters in green buildings by developing a universal driver interface for VOLTTRON™ platform

Expected Outcomes

- Enable interfaces for existing inverters to provide transactive services in a retrofit fashion and test the device functionality.
- A VOLTTRON™ -based development environment for transactive control grid-tied inverters

Progress to Date

- **Advanced VOLTTRON™ Control Platform**
  - Developed PE agent and its decision-making capability under various grid conditions
  - Developed dual closed-loop control strategy for VOLTTRON™ enabled hybrid driver interface
  - Evaluated advanced functions for grid-tied operation of inverter
- **Universal Hybrid Inverter Driver Interface**
  - Completed testing of hybrid interface with advanced functions
  - Evaluated hybrid driver interface with three different inverters to enable the inverters working with open source control platform

Significant Milestones	Date
Emulate functionality of advanced VOLTTRON™ platform to validate the control architecture	12/30/2016
Validate functionality of the hybrid interface using a commercial inverter	12/30/2017
Test the advanced VOLTTRON™ platform using the developed universal hybrid inverter driver interface	12/30/2018

Central Controller based on VOLTTRON™

Raspberry Pi

PE Agent

API-UDP

Universal Hybrid Driver Interface

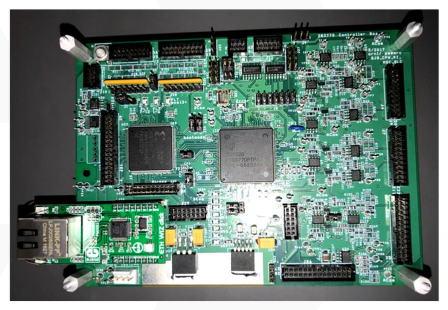
OAK RIDGE National Laboratory

Communication

Measurement

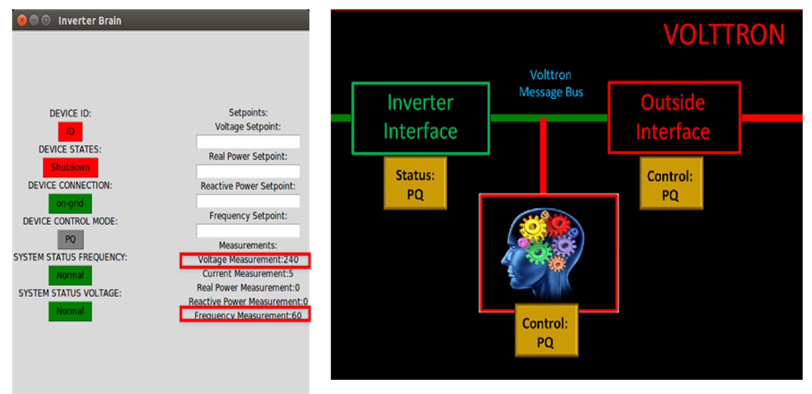
Calculation

PWM

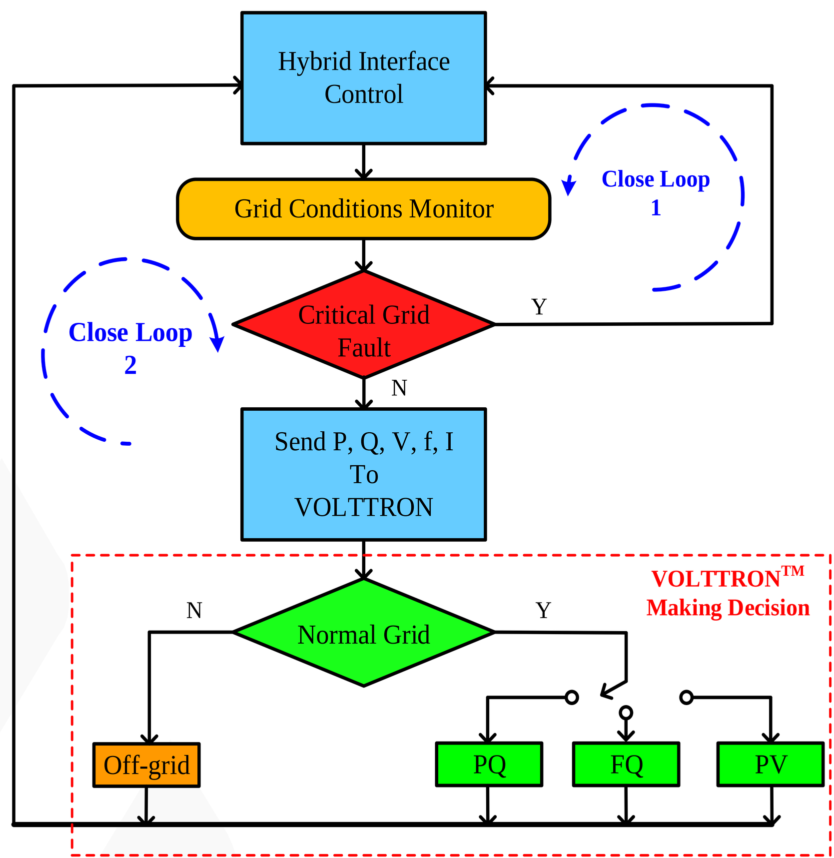


Direct Hardware Connection

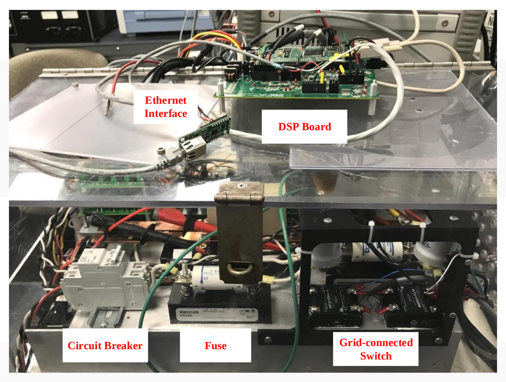
VOLTTRON™ PE Agent

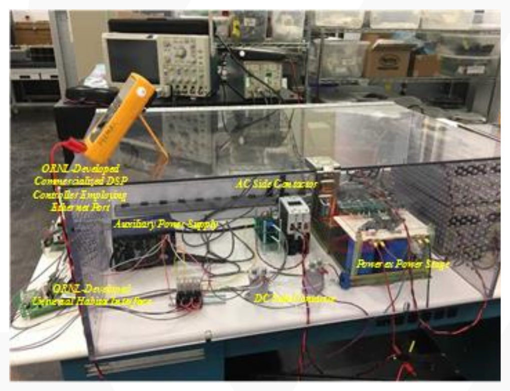


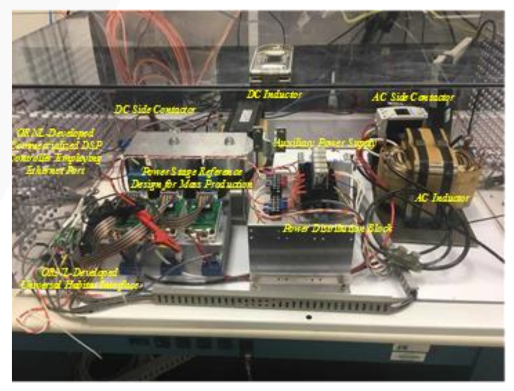
Software Flow Chart



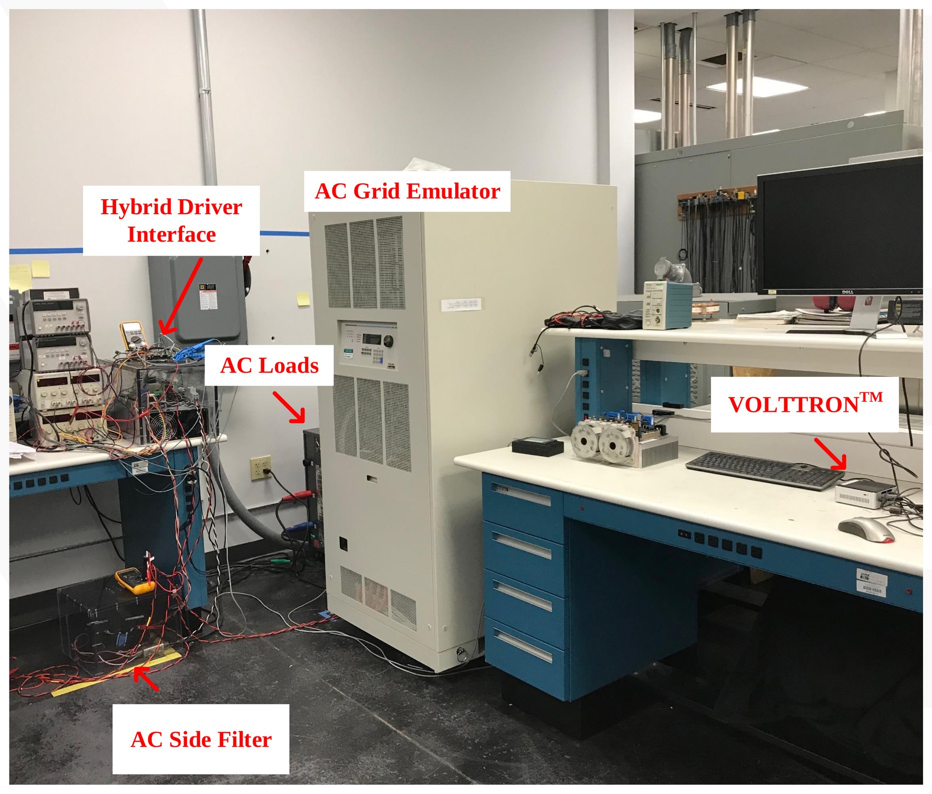
Power Stages fromThree Different Vendors



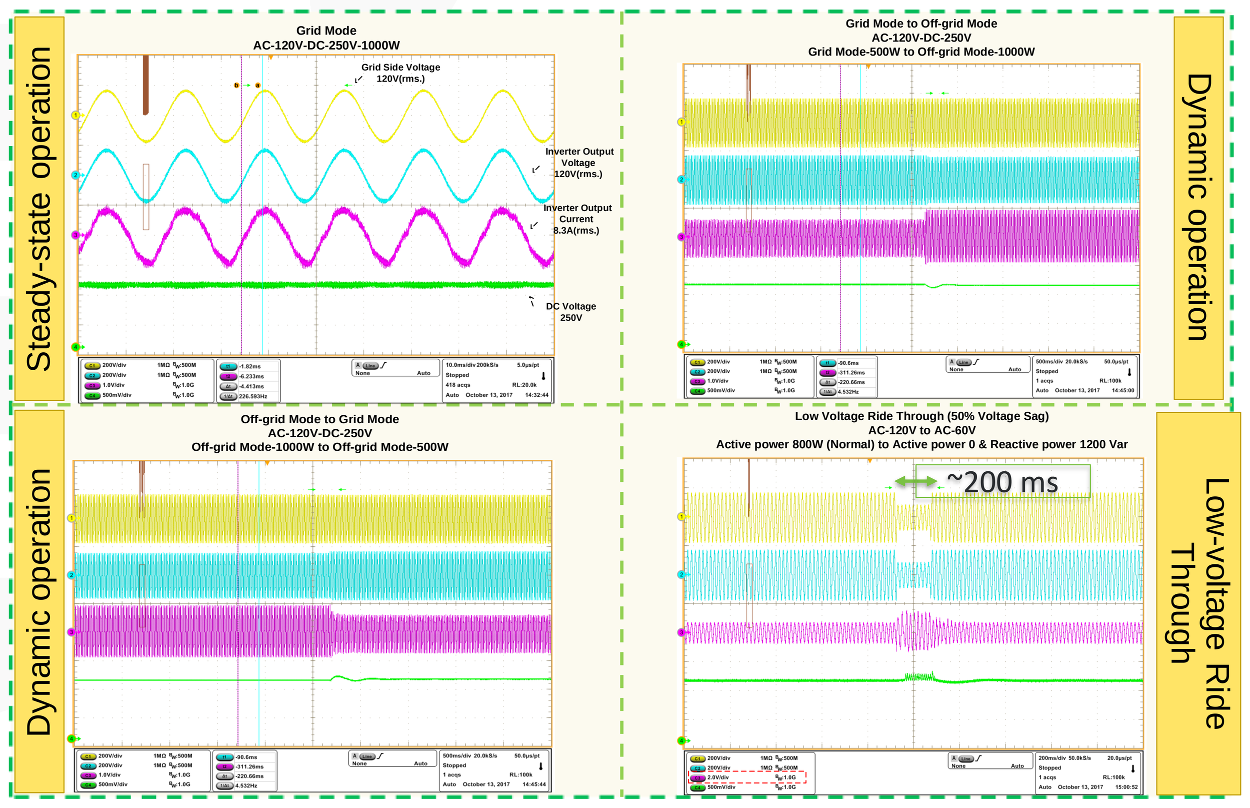




Interface Grid Test Bed



Test Results - Grid Test Operation



U.S. DEPARTMENT OF ENERGY

August 21, 2018

Testing and Modeling of HEMP and GMD Transients on High-Voltage Transformers

A. G. Tarditi[1], R. C. Duckworth[1], F. R. Li[3], Z. Li[1], Y. Liu[3], B. W. McConnell[1], R. G. Olsen[4], E. C. Piesciorowsky[1], B. R. Poole[2], L. Sundaresh[3], L. Wang[2],
[1]Oak Ridge National Laboratory, [2]Lawrence Livermore National Laboratory, [3]University of Tennessee Knoxville, [4]Washington State University
DOE Program Manager: K. Cheung

Context: HEMP and GMD as a potentially large-scale threat for critical, power grid components

High-altitude EM Pulse (HEMP): intense, short burst of EM energy originated by a nuclear explosion in the upper atmosphere. HEMP may affect a wide geographical area, couple to conductors, from power lines to electronic systems, and cause destructive voltage surges for a variety of electrical equipment.

Geomagnetic Disturbances (GMDs): strong, very low frequency fluctuations of the Earth magnetic field caused by ejected solar material that reach the Earth magnetosphere. GMDs may induce a quasi-*dc* current (Geomagnetic Induced Currents, **GICs**) on power lines, possibly leading to saturation of transformer magnetic cores that, in turn, may cause damages due to large harmonics generation and transformer overheating.

Project Description

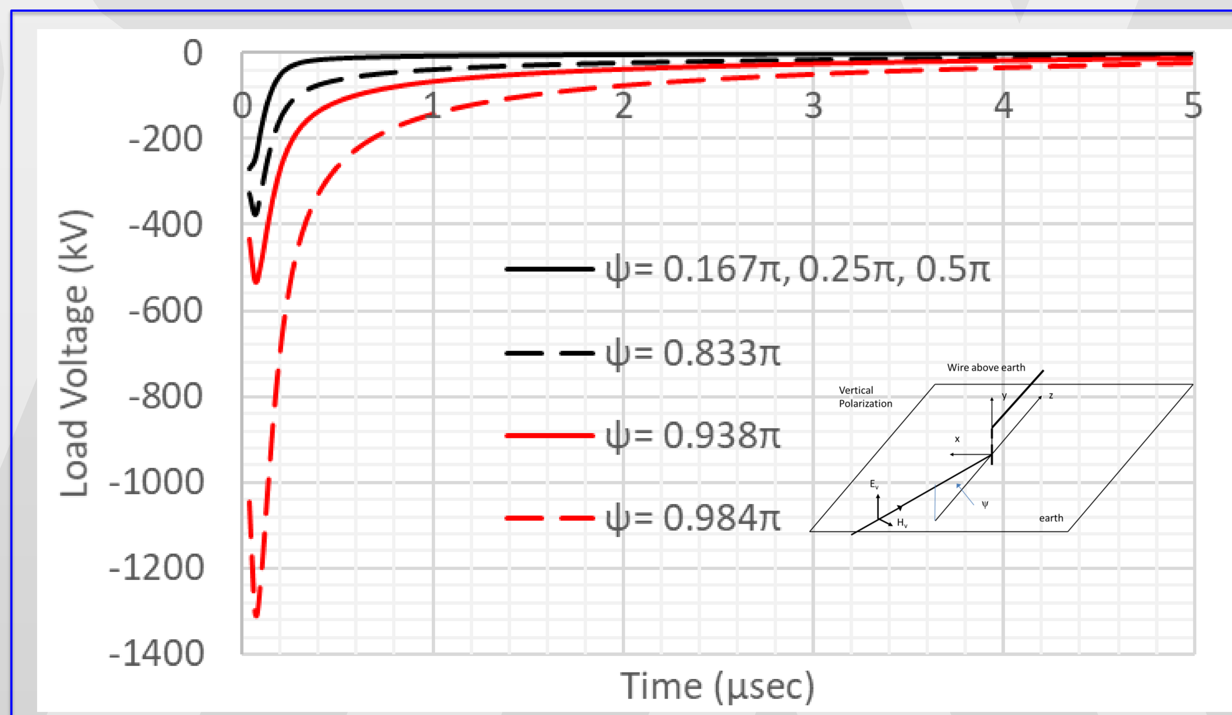
Quantitative analysis of specific knowledge gaps related to the risk of HEMP and GMD impact on high-voltage, power transformers (transmission-class), the most critical power grid assets. This work is aligned with the DOE current research thrust in support of the development of highly secure and resilient electric power infrastructure.

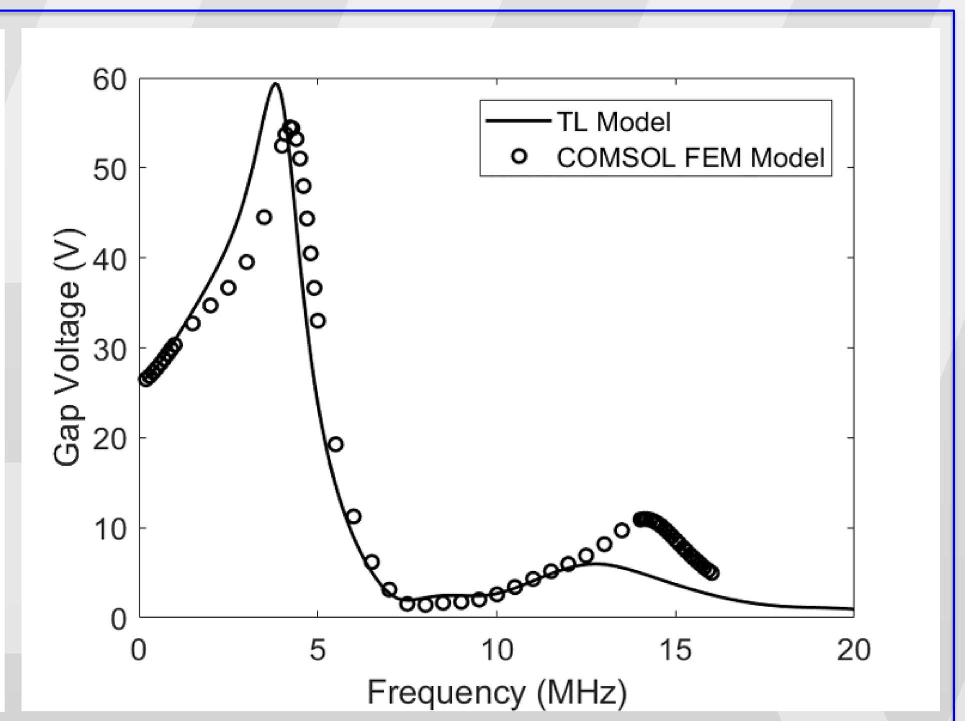
Expected Outcomes

- Technical guidance for industry and regulatory standards to provide risk mitigation of HEMP and GMD threats against the power grid
- Addressing quantitatively the EM vulnerability of large power transformers due to HEMP transients, fast-transient high-voltage (HV) arrester performances, and effectiveness of GIC countermeasures.

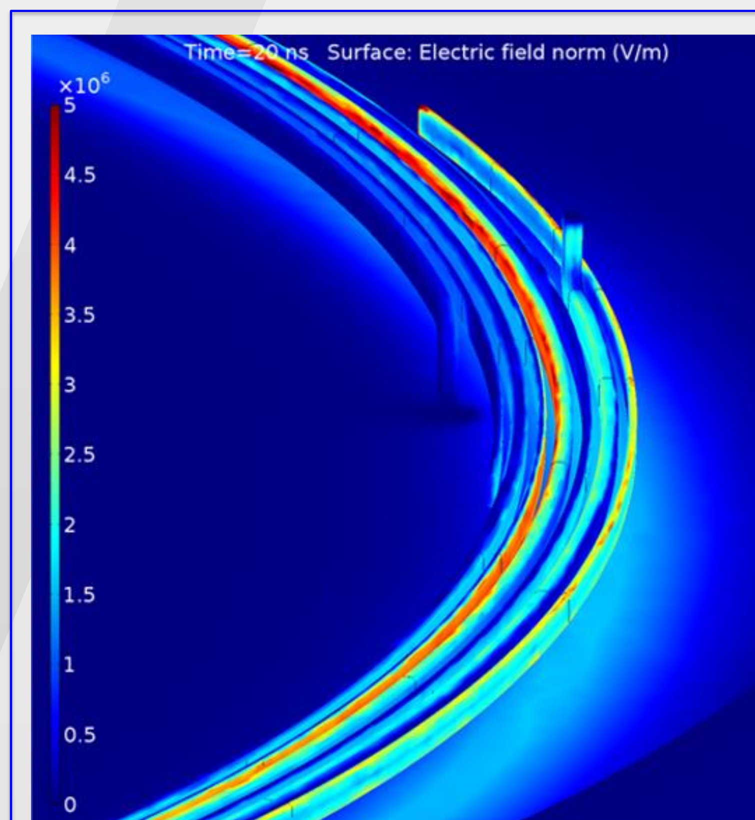
Progress to Date *(3rd Quarter Report: https://openpoint.nrel.gov/sites/gmlc/SitePages/Home.aspx)*

Significant Milestones	Date
HV arrester residual voltage under fast-transients	Q1-2018
First test models on system-wide implementation of GIC-blocking devices	Q2-2018
Quantitative assessment of HEMP coupling to power lines (IEEE Transactions paper)	Q3-2018

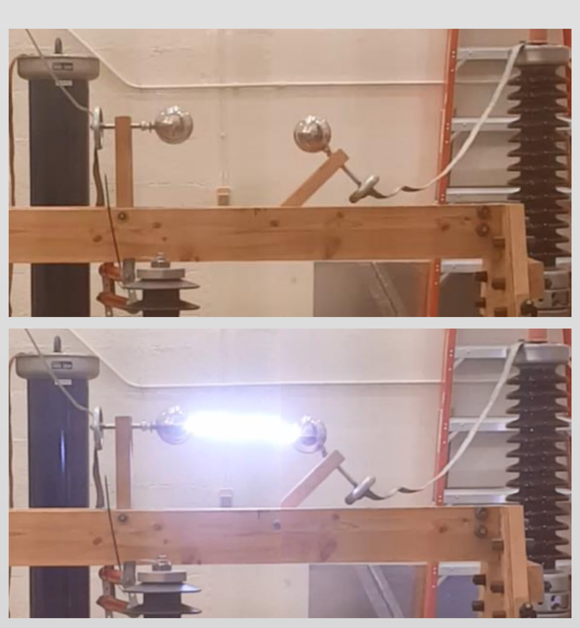


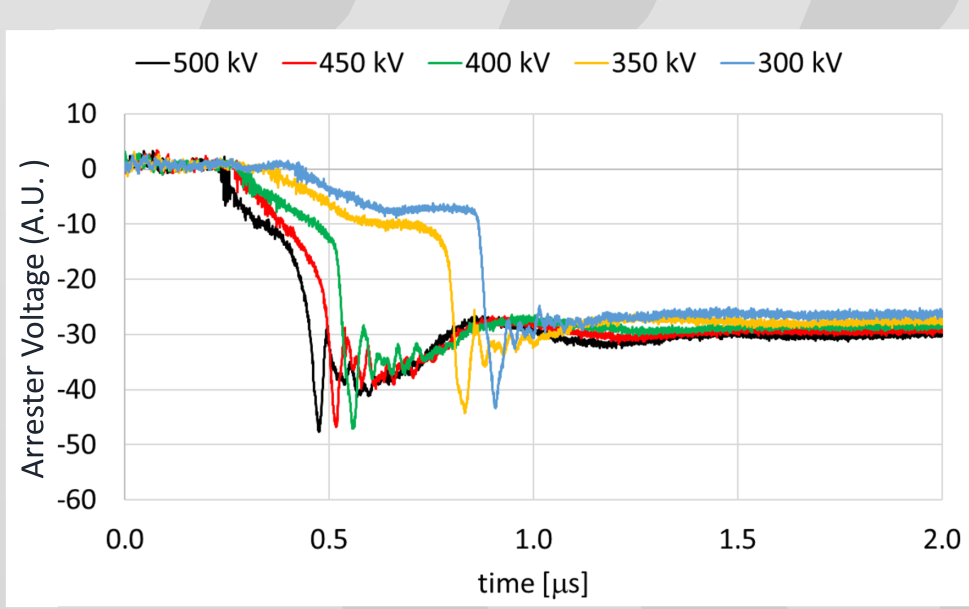


HEMP coupling to power lines (IEEE Trans. EMC and AMEREM 2018 Conference paper)
Induced voltage waveform on a loaded power line (left) and validation of HEMP-induced voltage vs. frequency (TL model vs. full EM model, right)

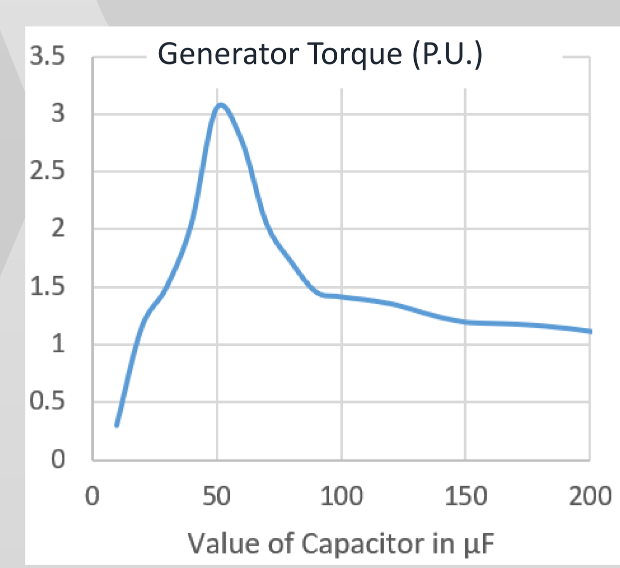


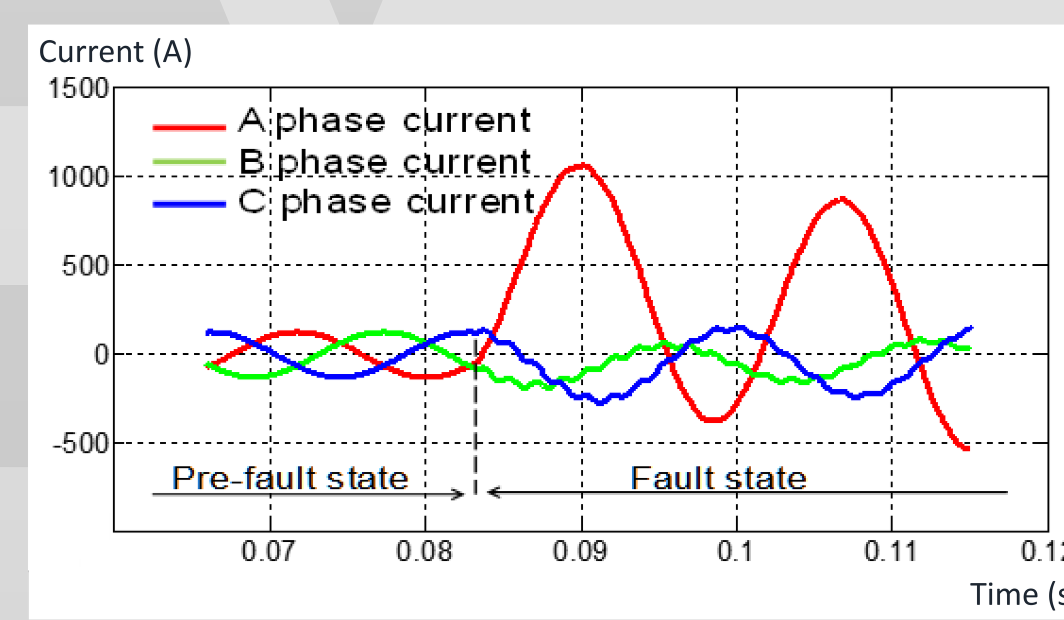
Transformer winding transient
COMSOL simulation of E-field from HEMP-induced waveform





Measure of HV arrester residual voltage under fast-transients, and accelerated aging setup
500 kV Marx pulsed discharge (overexposed photo, left), residual voltage before clamping (center), and arrester "aging" in 110º C heating furnace (right)





Feasibility of GIC countermeasures via capacitive dc-blocking
IEEE-benchmark for electro-mechanical impact from blocking capacitor on transformer neutral (left) and real-time simulator model of distance protection relay response during fault with GIC-blocking device inserted (right)

OE ADMS Program: Advanced Distribution Management System Testbed Development

Partnering Organizations: National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory, Argonne National Laboratory, Electric Power Research Institute, Holy Cross Energy, Xcel Energy, Opal-RT Technologies, Schneider Electric, GE Grid Solutions, Survalent

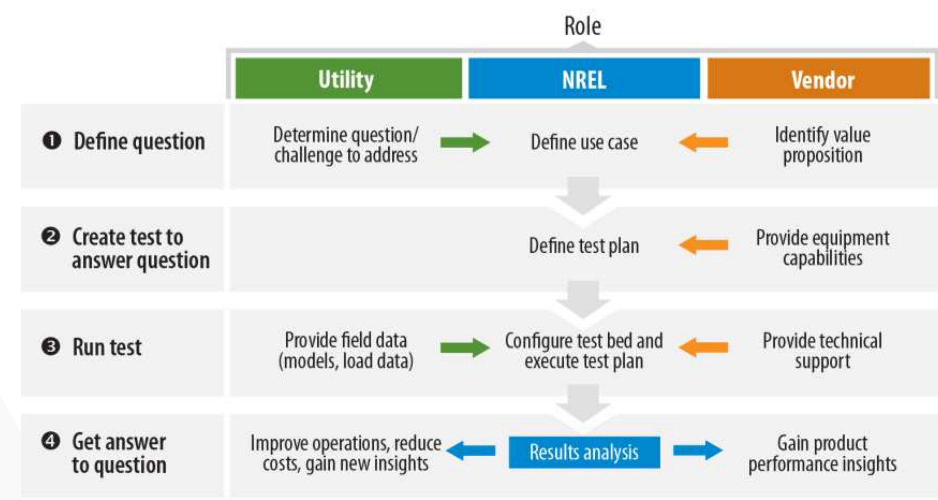
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY

AGR Program Specific Project

Project Description

- Model large scale distribution systems to support utilities and ADMS vendors in evaluating advanced distribution management system (ADMS) applications on realistic systems.
- Integrate distribution system hardware in NREL's Energy Systems Integration Facility for power and controller hardware-in-the-loop experimentation of key components.
- Develop advanced visualization capability to analyze the results for a mock utility distribution system operator's control room.

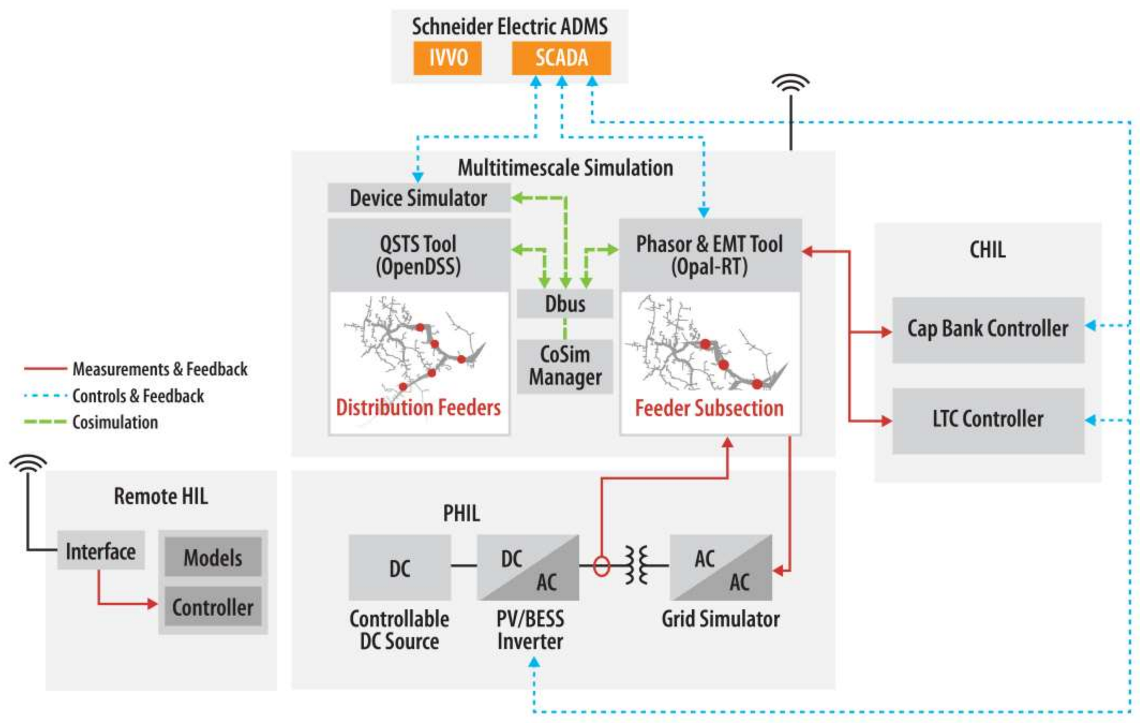


Model for utilities and vendors to use the ADMS testbed

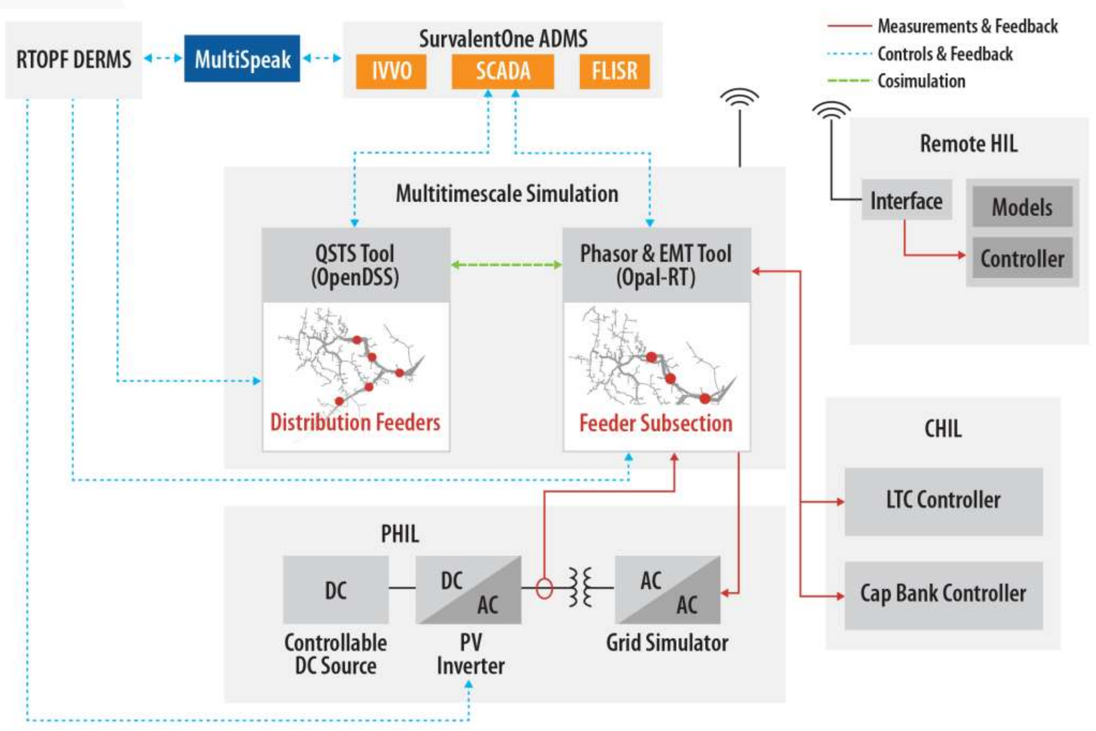
Power and controller hardware and visualization components

Expected Outcomes

- A vendor-neutral, pre-pilot testing ground for ADMS functionality that can be used by utilities and vendors to evaluate the benefits of an ADMS prior to investing in field deployments.
- Reduced risk for utilities and acceleration of ADMS deployments leading to more reliable and efficient distribution system operations.
- A test bed that will enable utilities and vendors to evaluate integration challenges of ADMS with legacy systems.
- A test bed that vendors can use as part of their development and evaluation of new ADMS applications.
- A facility for operator training of utility engineers.



ADMS testbed setup for Use Case #1: Data Remediation



ADMS testbed setup for Use Case #2: Integrated Peak Load Management

Significant Milestones	Date
Develop a testbed for ADMS using internal DMS power flow.	04/15/2017
Develop a test plan specifying tests to be conducted in Year 3.	10/15/2018
Execute the Year 2 test plan for use case #1 to show the impact of data remediation on the effectiveness of VVO.	10/15/2018
Host a workshop to disseminate the lessons learned in ADMS use case #1.	09/26/2018
Execute the Year 3 test plan for use case #2.	07/15/2019
Host a workshop to disseminate the lessons learned in ADMS use case #2.	07/15/2019

- Coordinating with other ADMS projects on a monthly basis to develop ADMS testbed capabilities to test the products on other projects.
- Established a combined IAB team for the platform and testbed projects.

Progress to Date

- Several Industry Advisory Board meetings held jointly with the GridAPPS-D project.
- ADMS testbed set up for use case #1:
  - Communication interface enabling co-simulation with OpenDSS and ePHASORsim by Opal-RT.
  - Power and controller hardware-in-the-loop.
  - ADMS with feeder models at different levels of data remediation.
  - Software tools to convert data files to OpenDSS and ePHASORSIM formats.
- Executed use case #0 (Integrated Volt-Var Control) using DMS internal power flow.
- Published four conference papers and journal article on use case #0 results in process.
- Use case #2 defined and partners identified.

Stabilizing the Grid in 2035 and Beyond

Evolving from Grid-Following to Grid-Forming Distributed Inverter Controllers

NREL (Lead): Y. Lin (PI), G. Seo, H. Villegas Pico
Team Members: B. Johnson (U. of Washington), F. Bullo (U. of California Santa-Barbara), S. Dhople (U. of Minnesota), P. Chapman (SunPower)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

- Historically, power grids have been constructed with interconnected generators with significant rotating mass or inertia. The collective inertia of generators enhances system stability and allows for the absorption of unpredictable load variations.
- In contrast, renewables such as PV rely on electronics with no moving parts. Thus, they are inertia-less.
- This project aims to develop distributed inverter controllers that provide a viable path from our existing infrastructure based on electromechanical generators to a highly distributed future grid dominated by electronic PV inverters with hundreds of GWs of PV integration.

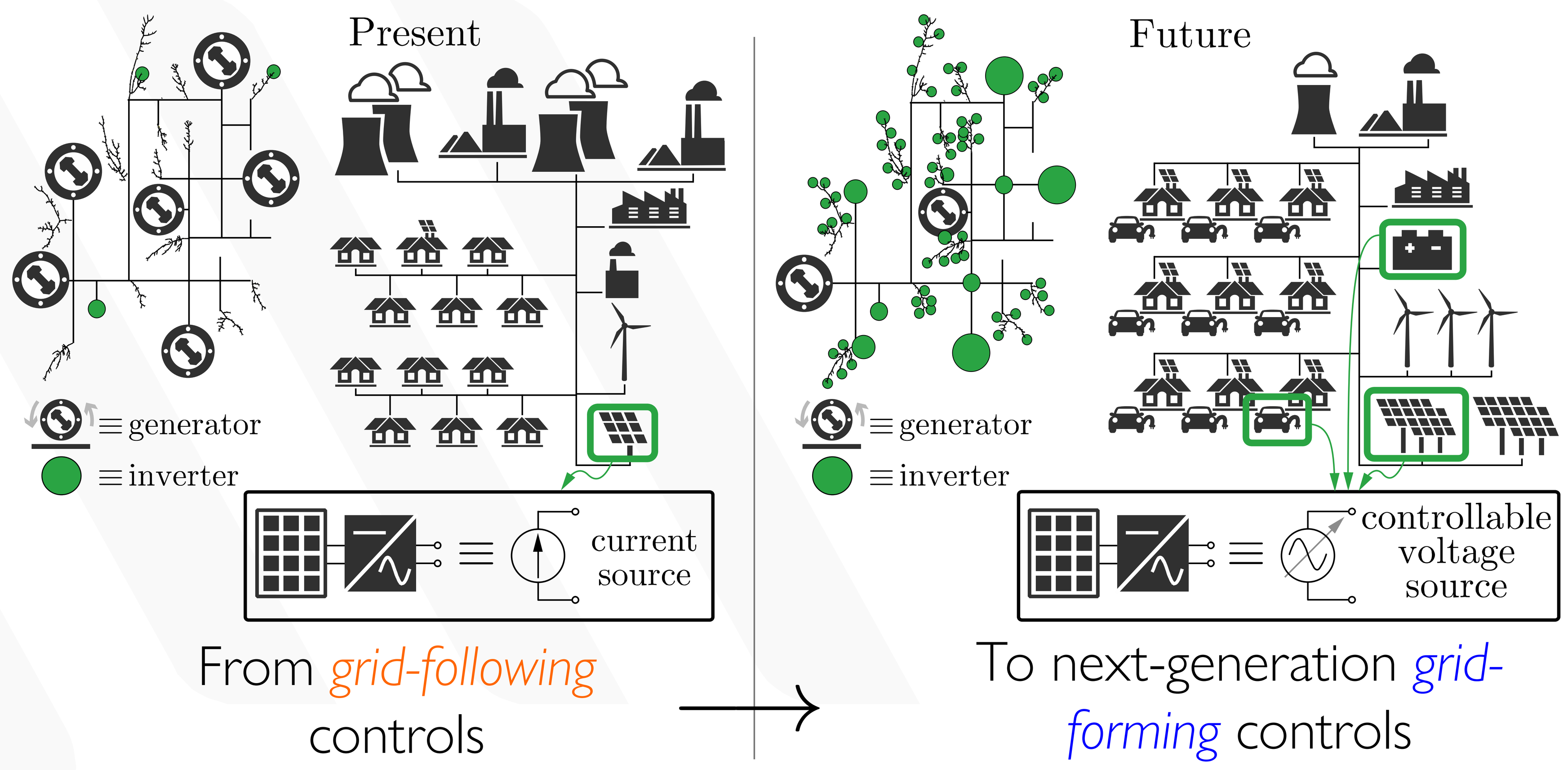


Fig.1 Evolving power systems.

Expected Outcomes

- Develop a new grid-forming strategy where inverters are controlled to emulate nonlinear oscillators; we call this virtual oscillator control (VOC).
  - *Impact: demonstrate the new grid-forming inverter control strategy has desired performance in low-inertia systems.*
- Develop a comprehensive modeling framework for stability assessment of low-inertia grids.
  - *Impact: provide a framework to evaluate the stability of combined inverter-machine systems.*
- Host a workshop on grid-forming inverter control.
  - *Impact: bring in experts from national laboratories, industry, and academic institutions together. Outline the state of art and future direction of grid-forming inverter technique.*

Significant Milestones	Date
Models for low-inertia multi-inverter networks.	09/30/2017
Framework and accompanying case studies for stability assessment of low-inertia grids.	09/30/2018
Workshop on grid-forming inverter control.	03/31/2019
Roadmap report that summarizes the state-of-art on grid-forming controls, future challenges, and industrial trends.	03/31/2019

Progress to Date

- Modeling framework for stability assessment of low-inertia grids:
  - Developed aggregation inverter model to represent a large collection of inverters.
  - Showed the stability can be lost for high penetration levels of grid-following units (business as usual case).
- Grid-forming inverter control strategy:
  - Designed, analyzed and implemented the VOC.
  - Leveraged partnership with SunPower to demonstrate new controllers with off-the-shelf commercial hardware.

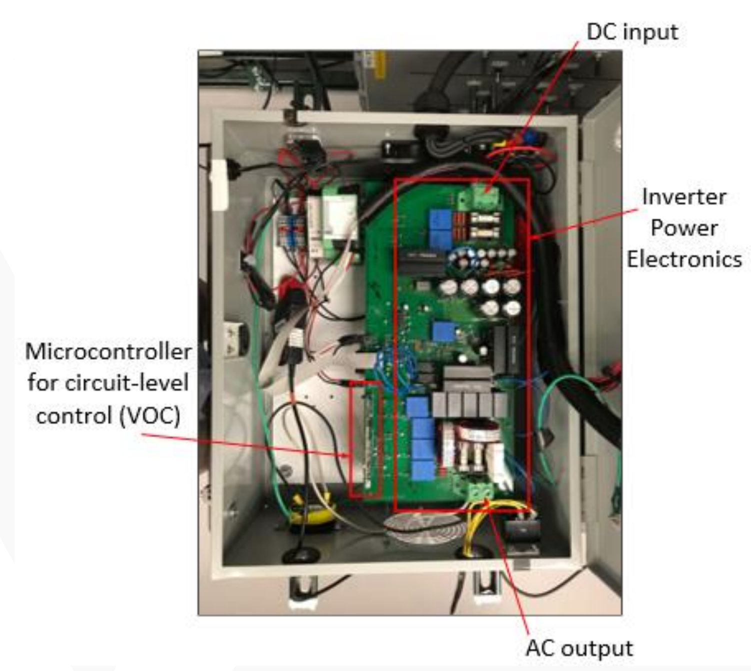


Fig.2 Customized VOC inverter.

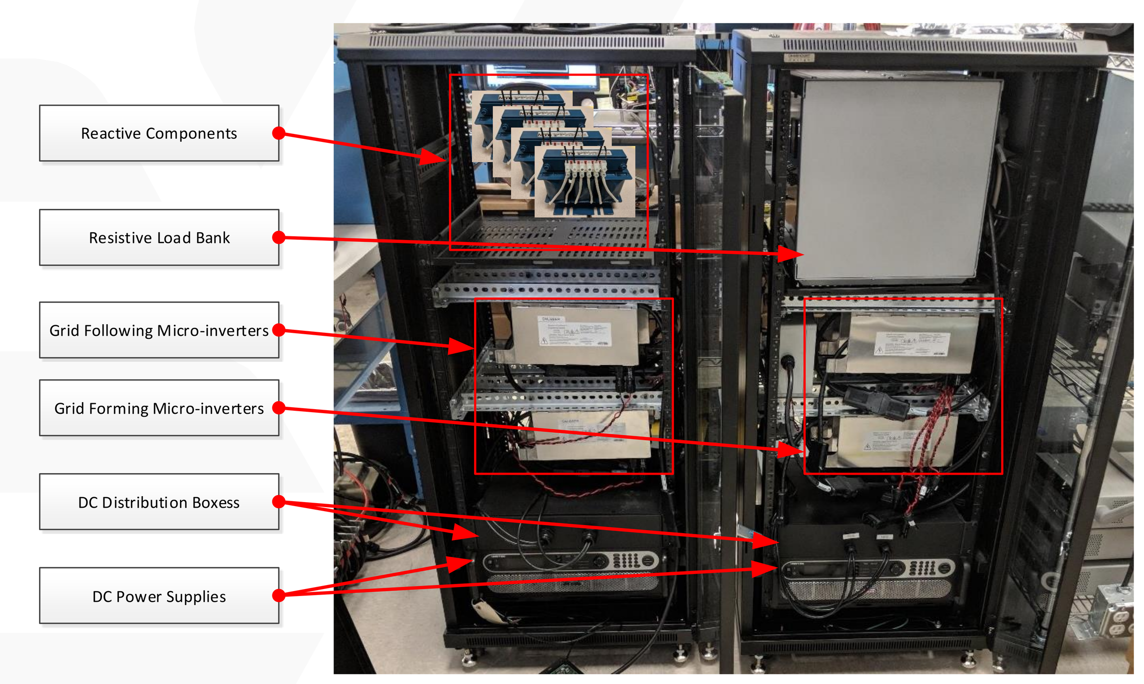


Fig.3 Testbed with SunPower Microinverters.

- Publications: 5 Journal Articles + 8 Conference Papers
- Visibility: Featured on IEEE Spectrum
- Intellectual Property: 3 Records of invention + 3 Patent application

Additively Manufactured Photovoltaic Inverter (AMPVI)

Lead: Oak Ridge National Laboratory
Team: National Renewable Energy Laboratory, Purdue University

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Develop a transformative PV inverter design approach based on **Additively Manufacturing** techniques and **Wide Bandgap (WBG)** semiconductor devices

Expected Outcomes

- Power density (*Inverter*): Alpha-10.4 W/in3, Gamma-14.5 W/in3
- Power density (*Power Block*): Alpha-75 W/in3, Gamma-114.5 W/in3
- CEC efficiency >98% (Alpha: 98.2%)
- Cost < $0.125/W
- Lifetime > 25 years
- Advanced grid support functions
- Communications capability
- More efficient reference design for PV industry
- Better grid stability / ancillary service for grid operators

Significant Milestones	Date
Achieved IEEE 1547 grid support functions, communications capability	6/30/2017
Achieved inverter power density 10.4 W/in3, efficiency 98.2%	9/30/2017
Achieved power density of the final power block greater than 75 W/in3	6/30/2018

SiC Power Block

- Genetic algorithm optimized thermal design
- 3D printed heatsink
- Advanced bare-die packaging technology

Control Platform

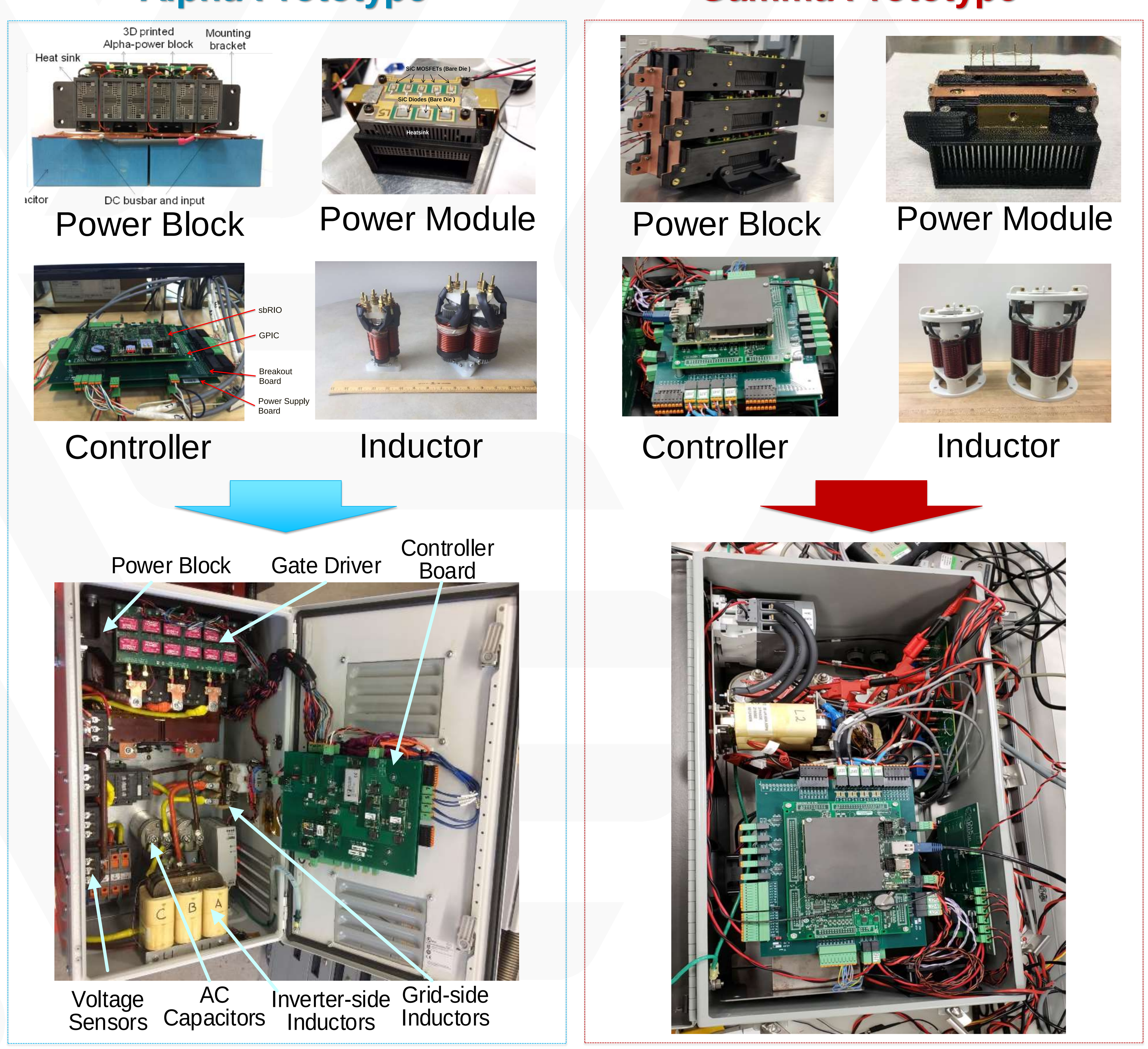
- Control / power hardware-in-the-loop
- Grid support functions (IEEE 1547 full revision)
- DNP3 or IEC 61850 communications

Magnetics

- Genetic Optimization System Engineering Tool
- Multi-objective parameter optimization
- Advanced magnetic materials and structures

Core Technology

Developed 50kW PV Inverter & Key Components



U.S. DEPARTMENT OF ENERGY

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Accelerating Systems Integration Standards (ACCEL)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

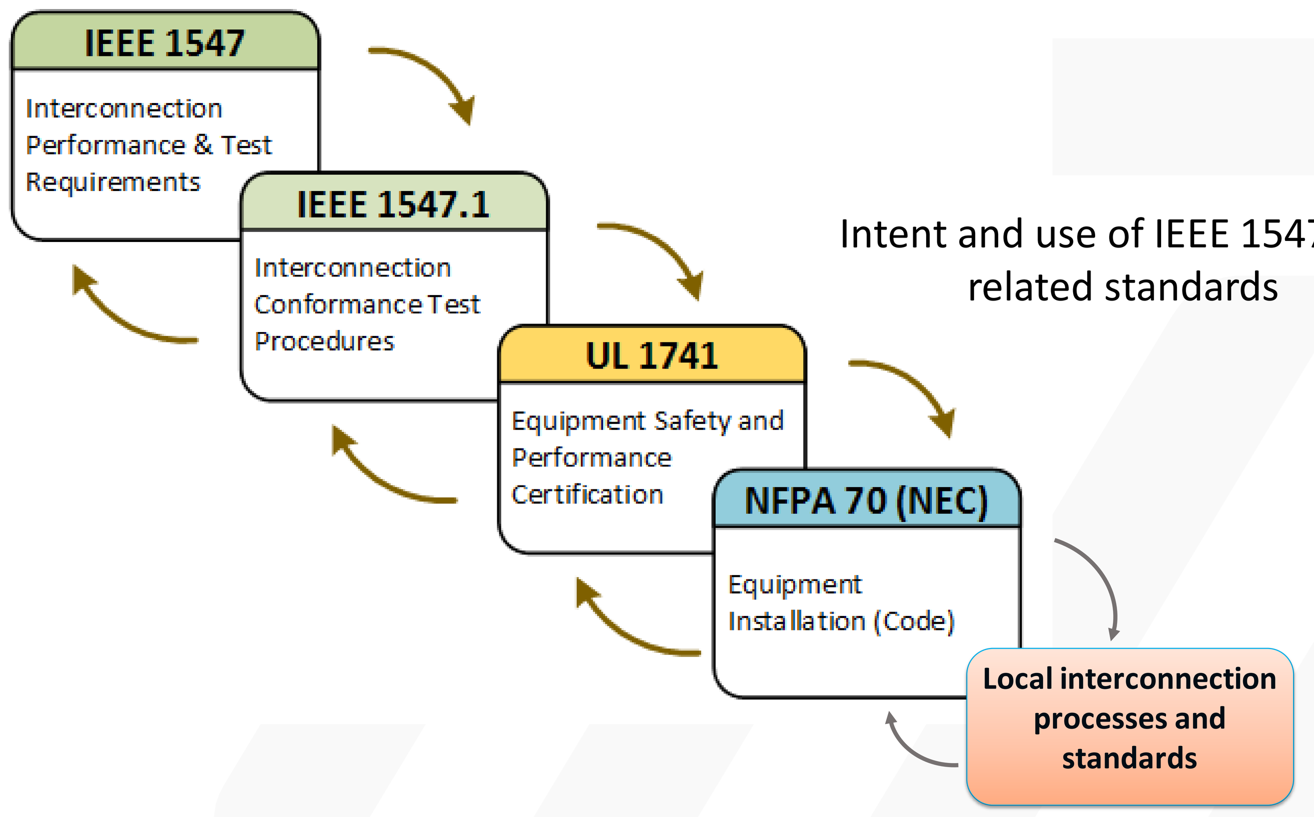
Updates to National Standards IEEE 1547, IEEE 1547.1, and UL1741 (30363)

Project Description

Establish **accelerated development** of new **requirements and conformance procedures** for distributed energy resource (DER) interconnection and interoperability for the full revision of IEEE 1547 (requirements), IEEE 1547.1 (test procedures), and UL 1741 update (safety standard).

Expected Outcomes

- Improved **harmonization between state and national** standards
- **Improved grid performance** under normal conditions
- **Increased electric grid resiliency** under abnormal conditions through new grid-support capabilities of modern DERs
- **Expanded markets** by maximizing feeder hosting capacity through increased optimization and interoperability capabilities of modern DERs



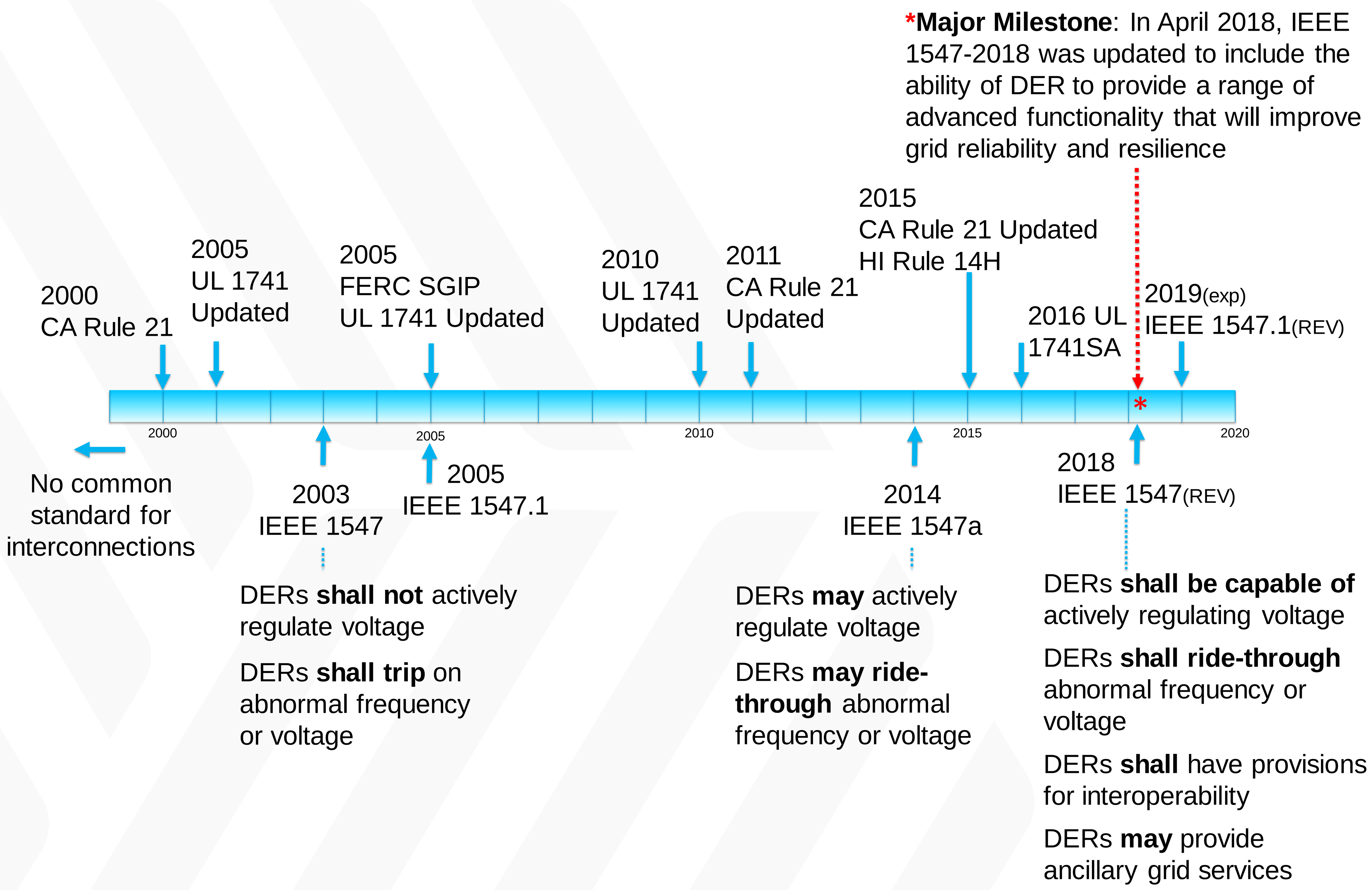
Intent and use of IEEE 1547 and related standards

Significant Milestones	Date
P1547 and P1547.1: Finalized officer team, working group, and topic subgroups	Oct 2015
UL1741SA: Published with revised (interim) test procedures	**Sep 2016**
P1547: Established new grid-support requirements, reached working group consensus	Feb 2017–Mar 2017
P1547: Recirculated final ballot—93% approval	Dec 2017
IEEE 1547-2018: Full revision published	**Apr 2018**
P1547.1 Draft 6 completed	Jun 2018

Partnering DOE Labs: National Renewable Energy Laboratory, Sandia National Laboratories

Industry Partners: IEEE 1547 and 1547.1 Working Groups

Timeline of improvements to interconnection standards



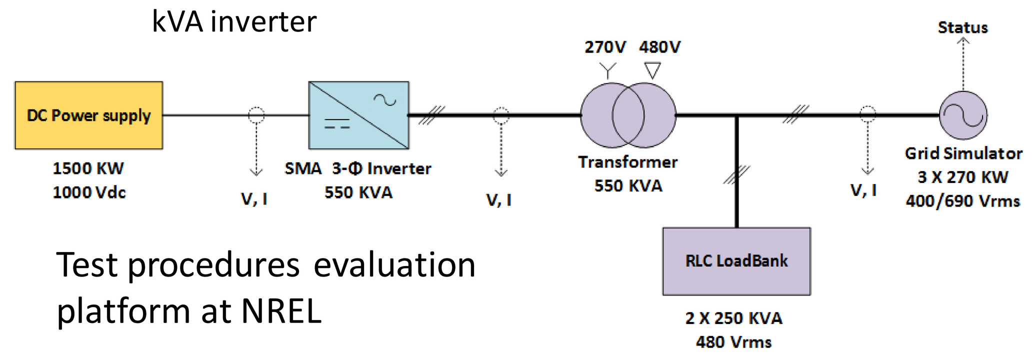
Progress to Date – Major Achievements

- **The DOE project team is providing leadership** at the officer level and the working group level, leading to tighter collaboration between P1547 and P1547.1, and sustained, focused effort towards building consensus among working group members.
- **121 industry experts** were part of the IEEE P1547 working group and **389 balloters** approved the revised IEEE 1547 standard by 93%.
- **NREL and Sandia testing facilities** and resources are being leveraged to exercise inverters and validate testing procedures for input to the working groups on device and testing requirements and functions. This supports the need to completely revise testing requirements to address new capabilities

Lab equipment at Sandia for evaluating conformance test procedures: Amtek 100kW PV simulator (left); AC simulator (right)

SMA Sunny Central CP-US 550-kVA inverter

Eaton 550-kVA transformer



Test procedures evaluation platform at NREL

U.S. DEPARTMENT OF ENERGY

GMLC SuNLaMP #31004: Combined PV / Battery Grid Integration with High Frequency Magnetics Enabled Power Electronics

Lead: National Energy Technology Laboratory
Partners: Eaton Corporation, North Carolina State University, Carnegie Mellon University, NASA Glenn Research Center

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

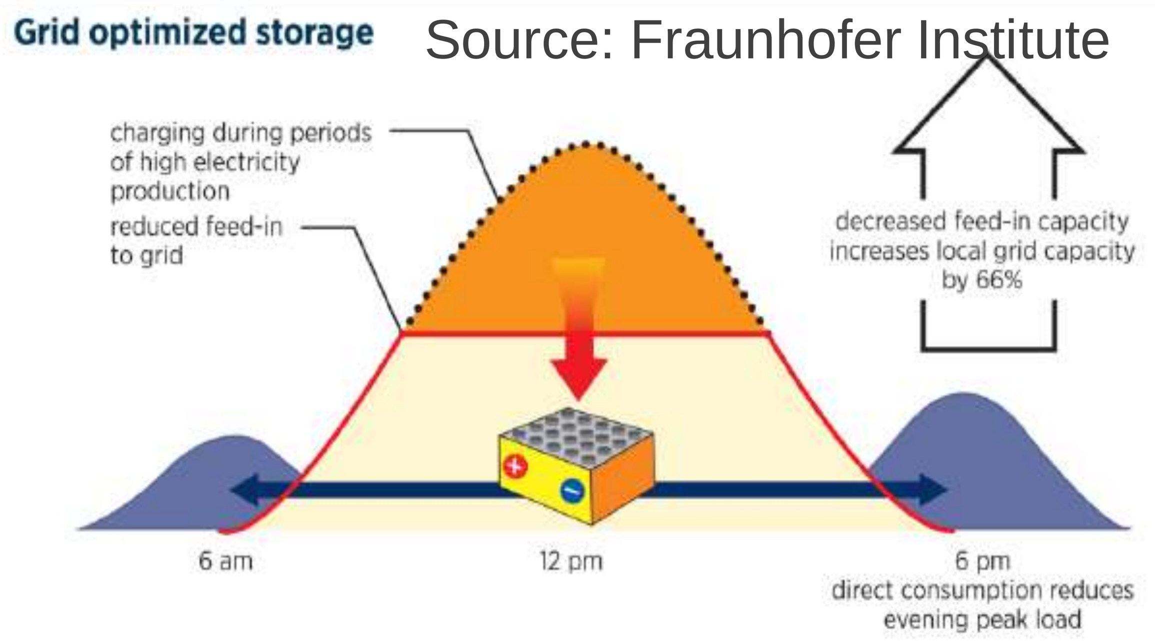
Project Description

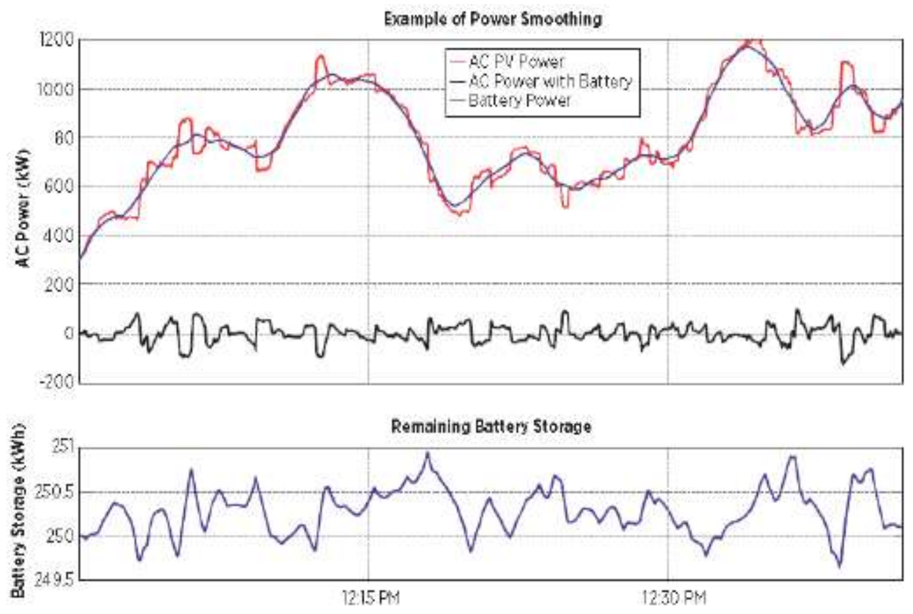
A novel approach to combined integration of solar photovoltaics and energy storage is being developed and demonstrated to mitigate against intermittency inherent to solar PV generation in a cost-effective, high efficiency, and power dense topology. Also core to this technology is the successful development of high frequency transformers for a multi-port DC-DC converter as well as implementation of wide bandgap based SiC switching devices.

Expected Outcomes

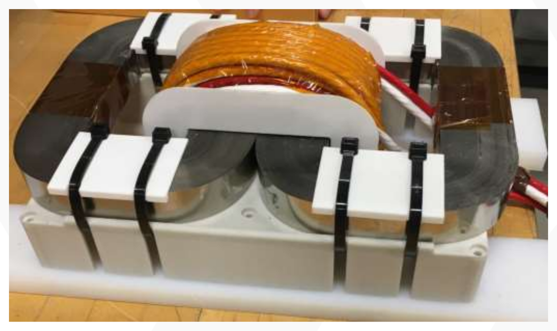
- Successful demonstration of 3-port DC-DC converter technology at 50kW (commercial) scale
- System level studies of feasibility for utility scale (>1MW) and compatibility with interoperability requirements
- Development of new enabling magnetics technology for the next generation of high frequency transformers
- Technology transfer of intellectual property and know-how to the private sector to promote near-term commercialization
- Successful completion of these outcomes will enable greater penetration of solar generation through simultaneously:
  - Reducing costs, increasing power density, and increasing reliability of grid interconnection hardware
  - Successfully managing inherent variability of solar

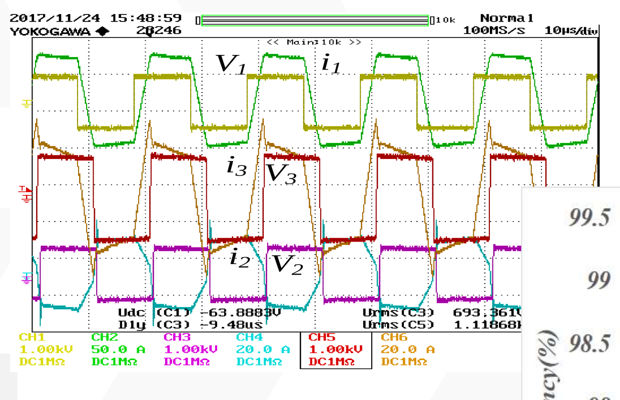
Significant Milestones Completed	Date
Successful prototype demonstration and design of a 50kW high frequency transformer architecture.	12/31/2017
Successful prototype demonstration and design of a 50kW DC-DC converter architecture within project metrics.	3/31/2018
Simulation of 1MW series and series-parallel connected grid tie inverter architectures to demonstrate compatibility with interconnection / interoperability standards.	3/31/2018
Successful demonstration of "permeability engineered" magnetic cores for the first time with reduced losses and peak temperature rise during steady state operation.	12/31/2017
Establishment of new magnetic core processing and testing capabilities for full-scale transformer build and test.	12/31/2017

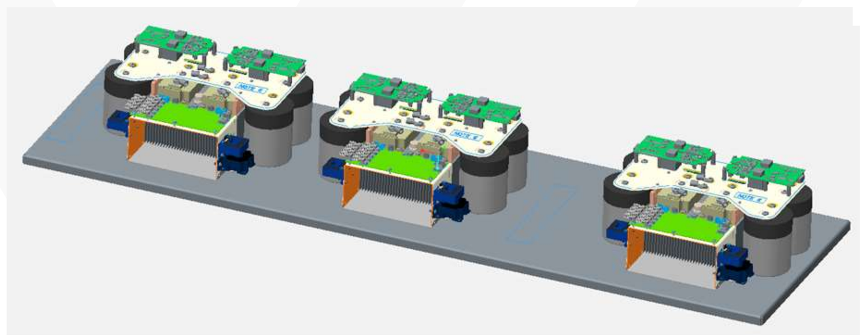


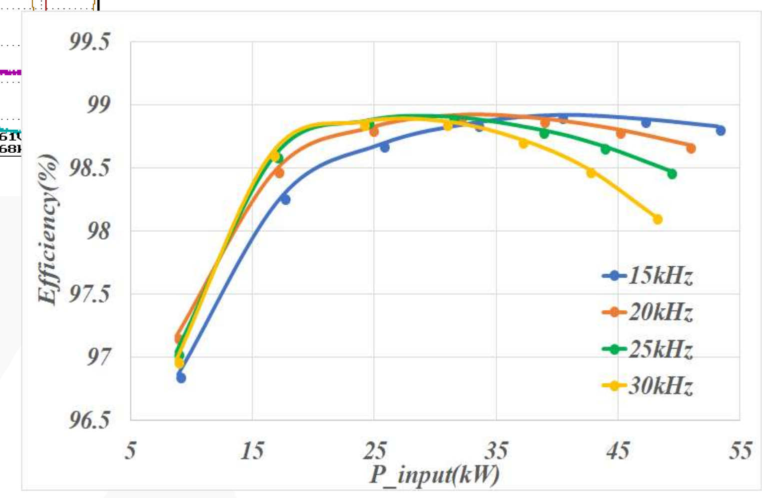


Combined Solar PV / Energy Storage Integration Has Inherent Advantages Including "Energy Time Shift" and "Power Smoothing".

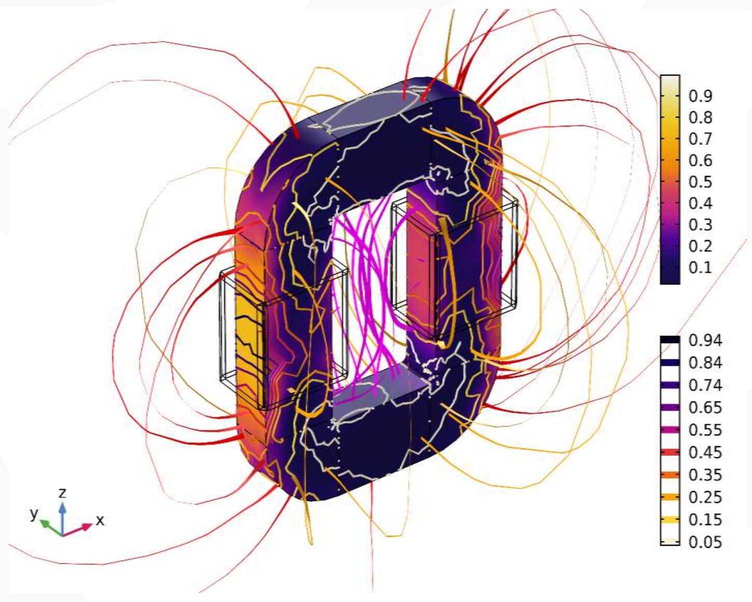


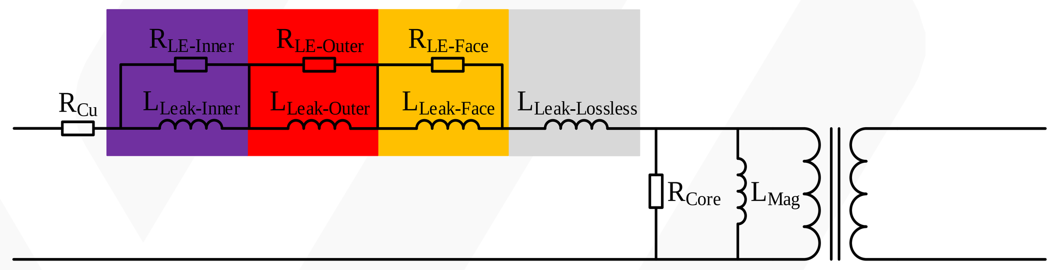


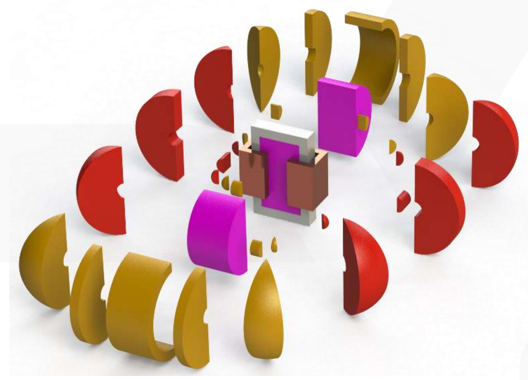




Successful 50kW Prototypes of a Full 50kW transformer (top) and the rendering of 3-Port 50kW DC-DC Converter Hardware (bottom). Waveforms Showing Effective Power Flow and Efficiency Estimates for Various Prototypes are also Presented (right).







Newly developed models of losses and performance of transformers with advanced core materials for advanced transformer design.

Progress to Date

- Successful 50kW Demonstrations
- Successful interconnection of multiple DC-DC converters in series at the 10kW level, scaling to 50kW underway
- Full inverter simulations demonstrating compatibility with grid interconnection requirements and standards
- New Transformer Fabrication, Testing, and Modeling Capabilities
- Numerous publications, patent applications, and presentations.
- Technology transfer efforts underway with manufacturing partner for enabling magnetic alloys and processing technologies.

Power System Reliable Integration Support to Achieve Large Amounts of Wind Power (PRISALA)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Provide key stakeholders in power system planning and operations access to best practices for integrating wind energy that are built on actual experience and analysis/modeling

Expected Outcomes

- Provide unique access to credible information and applied research to facilitate wind energy integration
- Ensure that state-of-the art results, methods, and data in wind integration reach critical decision-makers
- Support and provide leadership to the Energy Systems Integration Group (ESIG, formerly UVIG), the leading technical organization in the U.S. for advancing the state of knowledge of energy systems integration
- Work closely with the North American Electric Reliability Corporation (NERC) on their Essential Reliability Services Working Group to ensure that key reliability issues are addressed for America's future power grid and also with NERC on their Frequency Response Study to make sure that adequate frequency response is available in all U.S. Interconnections

Significant Milestones	Date
• Complete paper "Revenue Sufficiency and Reliability in a $0 Marginal Cost Future"	12/30/2016
• Participate in NERC Essential Reliability Services Working Group	6/30/2017
• Support and participate in ESIG Spring Technical workshop	6/30/2018

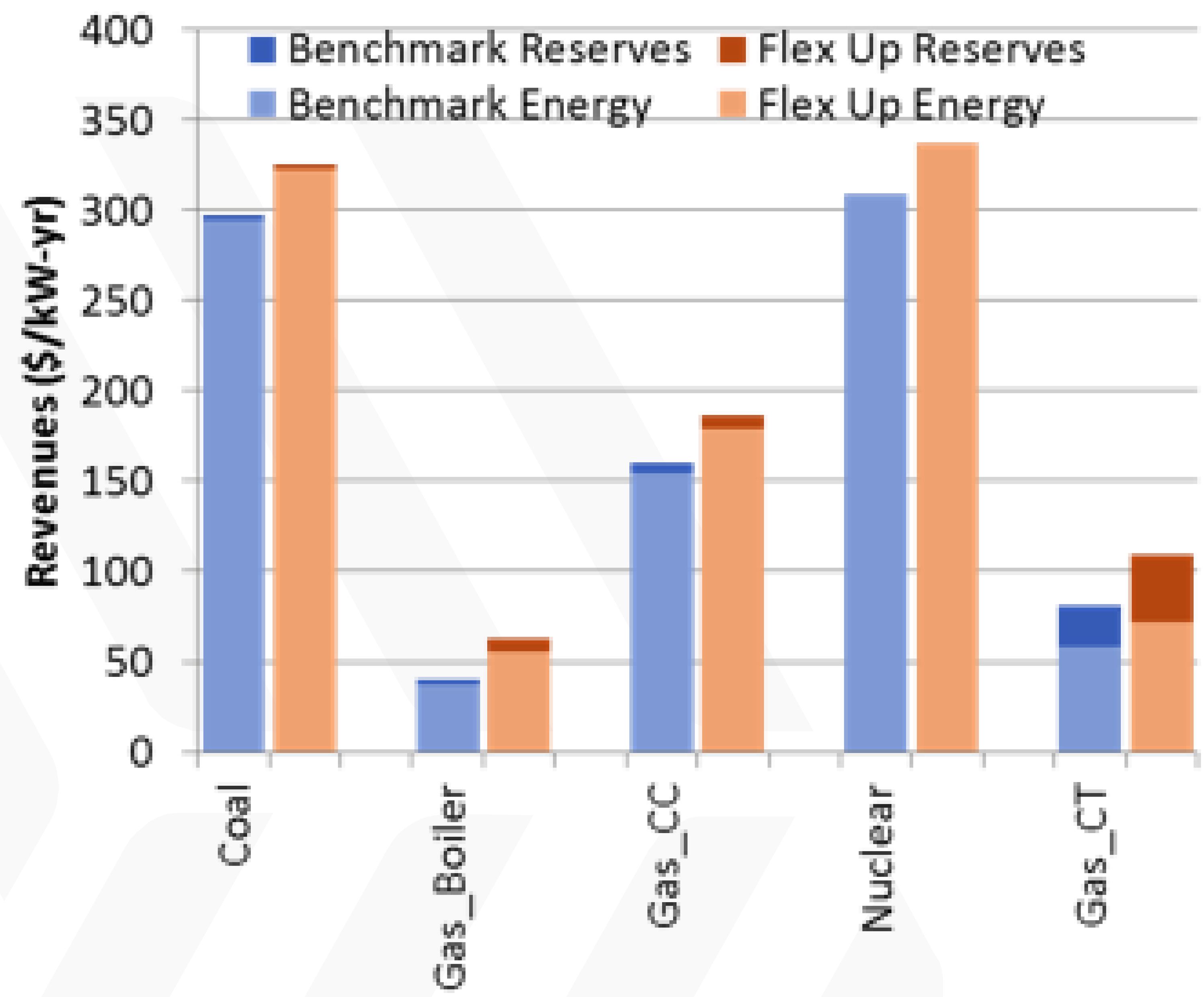


Figure 1. Total revenues for the 2013 Benchmark and Flex Up scenarios - from *Revenue Sufficiency and Reliability in a $0 Marginal Cost Future* paper

Progress to Date

- Participate in NERC Essential Reliability Services Working Group
- Participate in NERC Frequency Response Study
- FERC briefings including presentation on the Eastern Renewable Generation Integration Study
- Leadership of IEA Task 25 (Design and Operation of Power Systems with Large Amounts of Wind. Power")
- National Association of Regulatory Utility Commissioners (NARUC) presentations
- Presentations of key wind integration findings at ESIG
- Capacity Value Assessments for Wind Power: An IEA Task 25 Collaboration. Milligan, M., B. Frew, E. Ibanez, J. Kiviluoma, H. Holttinen, L. Söder. Wiley Wires. 2016